Case Studies of Naturally Ventilated Commercial Buildings in the United States

by

Jui-Chen Chang

S.B., Mechanical Engineering (2000)

Massachusetts Institute of Technology

Submitted to the Department of Mechanical Engineering
In Partial Fulfillment of the Requirements for the Degree of
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Signature of Author..
Department of Mechanical Engineering
May 10, 2002

Certified by..
Leon R. Glicksman
Professor of Building Technology and Mechanical Engineering
Thesis Supervisor

Accepted by..
Ain A. Sonin
Chairman, Department Committee on Graduate Students

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ABSTRACT

During the fall of 2000, an extensive search for purpose-built, naturally ventilated non-residential buildings, in the eastern United States, was conducted. This search revealed very few buildings suitable for field monitoring. Out of a very narrow field, two buildings were selected.

The smaller of the two buildings selected is the Broadmoor Wildlife Sanctuary's nature center. The building is a retrofitted barn in the town of Natick, Massachusetts, located 15 miles west of Boston. The architect leading the 1983 retrofit was Gerard Ives, known for promoting passive solar concepts in his work. The building features two occupied floors of approximately 5,600 square feet of total area. The building is wholly naturally ventilated, coupled with the use of passive solar heating during the winter.

The second of the two buildings is the Chesapeake Bay Foundation's Philip Merrill Environmental Center, located in Annapolis, MD. The building, designed by the Washington DC branch of SmithGroup, opened in December of 2000. It was the first building to receive a Leadership in Energy and Environmental Design (LEED) Platinum rating. Approximately 80 full-time workers occupy two floors over approximately 32,000 square feet of area. Natural ventilation was specified for usage approximately 9% of the year and is available through a mixture of automated and manually operated windows.

Portable temperature and humidity loggers were placed in each building. Outdoor weather conditions, including wind speed and direction, were recorded from on-site weather stations. During weekly to monthly site visits, air velocities, surface temperatures, and other parameters were also measured. To determine thermal comfort, occupants were asked to rate their thermal sensation in daily surveys.

Data collected from both buildings was compared to a basic single-zone thermal and airflow model. It was originally hypothesized that the results might not be very accurate; yet, the results show no more than 10% error for the data analyzed. It is hoped that architects can use this basic model for pre-design evaluation of natural ventilation usage, with an understanding of the benefits, as well as the limitations.

Natural ventilation turns out to be used effectively in both buildings studied, both in maintaining thermal comfort and lowering overall energy consumption. A discussion of Simmons Hall, a new MIT undergraduate dormitory scheduled for opening in the fall of 2002, is also included.

Thesis Supervisor: Leon R. Glicksman
Title: Professor of Building Technology and Mechanical Engineering

Table of Contents

Table of Figures

Background

Danish Magister Union

Roskilde University

Sofiendal School

Main Tower

Victoria Insurance Tower

RWE Tower

Stadttor Dusseldorf

European Patent Office

Inland Revenue Castle Meadows

Jubilee Campus

Queens Building

Edinburgh Gate

BRE Environmental Building

Broadmoor Wildlife Santuary Nature Center

Chesapeake Bay Foundation Phillip Merrill Environmental Center

Simmons Hall

Model Fundamentals

Thermal Comfort

Broadmoor Wildlife Sanctuary Results

Phillip Merrill Environmental Center Results

List of Tables

Background

Broadmoor Wildlife Sanctuary Nature Center

Chesapeake Bay Foundation Phillip Merrill Environmental Center

Simmons Hall

Model Fundamentals

Broadmoor Wildlife Sanctuary Results

Phillip Merrill Environmental Center Results

Appendix

Acknowledgements

I would like to thank my parents and my sister for their unwavering support of my education. As I prepare to move onto another phase of my life, reflections on the past reaffirm the importance of my family in my successes. Mom, Dad, and Connie, I dedicate this thesis to you.

I would also like to thank the friends that have supported me throughout my years at MIT. Special thanks go to Jonathan Wang and Ruth Perlmutter for always finding time for me, even when things were busy in their own lives.

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Lastly, I would like to thank the Kann-Rasmussen Foundation for generously sponsoring this research project.

Chapter 1 Background Information

1.1 Introduction

Commercial buildings play a major role in society. They are buildings that house businesses of all types, whether they are research organizations, financial powerhouses, or consulting firms. Vital to the success of these organizations is the ability of their buildings to provide a comfortable and healthy working environment. Before the 1950s, natural ventilation and daylighting were used to achieve this, sometimes in innovative ways based purely on common knowledge and sense. Eventually, artificial lighting and ventilation gained dominance to the point where they are now the norm in the United States [Arnold, 1999].

A similar trend occurred in Europe, but not to the same degree as in the United States. This happened for many reasons, including a more widespread cultural concern for increased electricity consumption, coupled with a desire for a connection to the natural environment. Research on this topic over the past decade has blossomed, in part due to a significant number of architecturally recognized buildings developed by the European design community [Allard, 1996; Kukadia, 1998; Liddament, 1998; Santamouris, Argiriou, & Deschamps, 1996; Santmouris & Asimakopoulous, 1996]. These buildings attempt to go beyond what was done decades ago, in an effort to create low-energy buildings that set benchmarks for future building construction [Allard, 1998; BRE, 1999; CIBSE, 1998; Perera, 1998]. The majority of these buildings have been constructed in central and northern Europe, where the climate is very similar to the climates of several regions in the United States [Axley, 2001]. This leaves the question of why natural ventilation is so rare in the United States.

The research presented in this thesis hopes to shed some light on natural ventilation in the United States. Beforehand, we present information on what natural ventilation is and the known advantages and disadvantages. A discussion of European buildings visited in 2000 will also be presented.

1.2 Description of Natural Ventilation

Natural ventilation can be used for several purposes. The first is to control the air quality of a space, by exchanging stale air with fresh outdoor air. The second is to provide direct cooling to a particular space, by replacing warm indoor air with cooler outdoor air without chillers, thus reducing overall energy consumption. Lastly, natural ventilation can provide indirect night cooling to a building's thermal mass.

1.2.1 Cross Ventilation

Cross ventilation relies on wind pressure to force air through a building, usually through vents and windows located on opposite sides of the building. Cross ventilation thus requires that a building's plan be open to allow air to flow unrestricted. The depth of the building must also be contained, so that ventilation is able to remove heat and pollutants. A building should be sited according to predominant winds, with attention paid to surrounding features, such as trees, bodies of water, other buildings, and other objects that may influence airflow [ASHRAE, 1997].

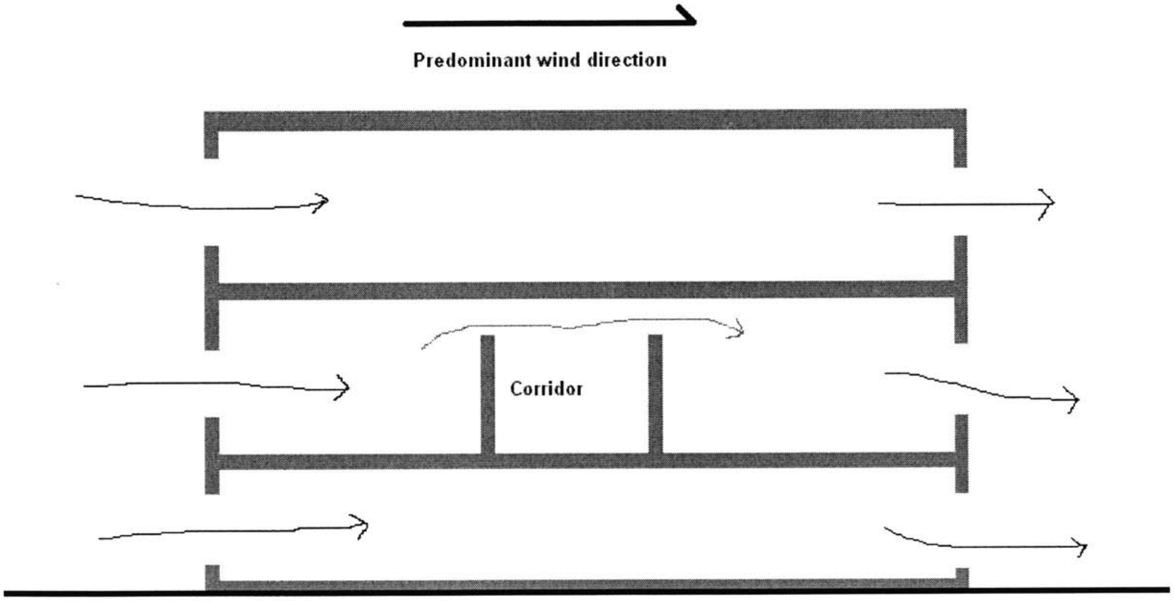


Figure 1 Diagram of cross ventilation.

1.2.2 Stack Ventilation

Stack ventilation relies on density differences to move air from a location of low temperature to a location of higher temperature. As temperature increases, the density of air decreases, typically forcing air to move upwards. A chimney or atrium is often used to generate sufficient pressure, through the stack effect, to force air through a building's envelope. Slight wind pressure can also induce airflow as shown in the diagram below. Stack ventilation is particularly well suited for cases when there is little or no wind.

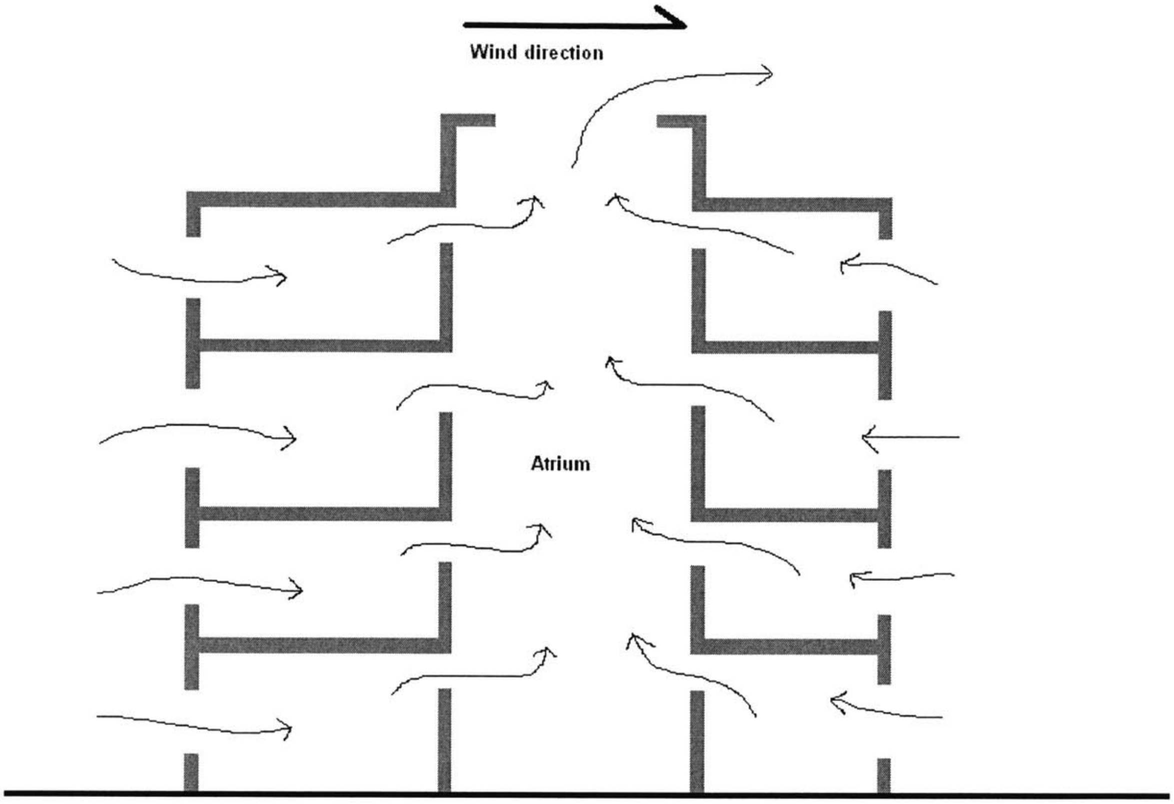


Figure 2 Diagram of thermally-driven natural ventilation.

1.2.3 Single-sided Natural Ventilation

Single-sided ventilation is typically used when cross ventilation is not possible, due to the desire to isolate various rooms for privacy or to satisfy fire regulations. Single-sided ventilation relies on smaller-scale buoyancy effects that are dictated by a difference in indoor and outdoor temperature. Air will enter through a low opening in a room, heat up and rise due to internal loads, and then exit through openings high in the room. It should be noted that single-sided ventilation is not the ideal natural ventilation strategy. Typically, the highest air change rates are achieved with cross ventilation.

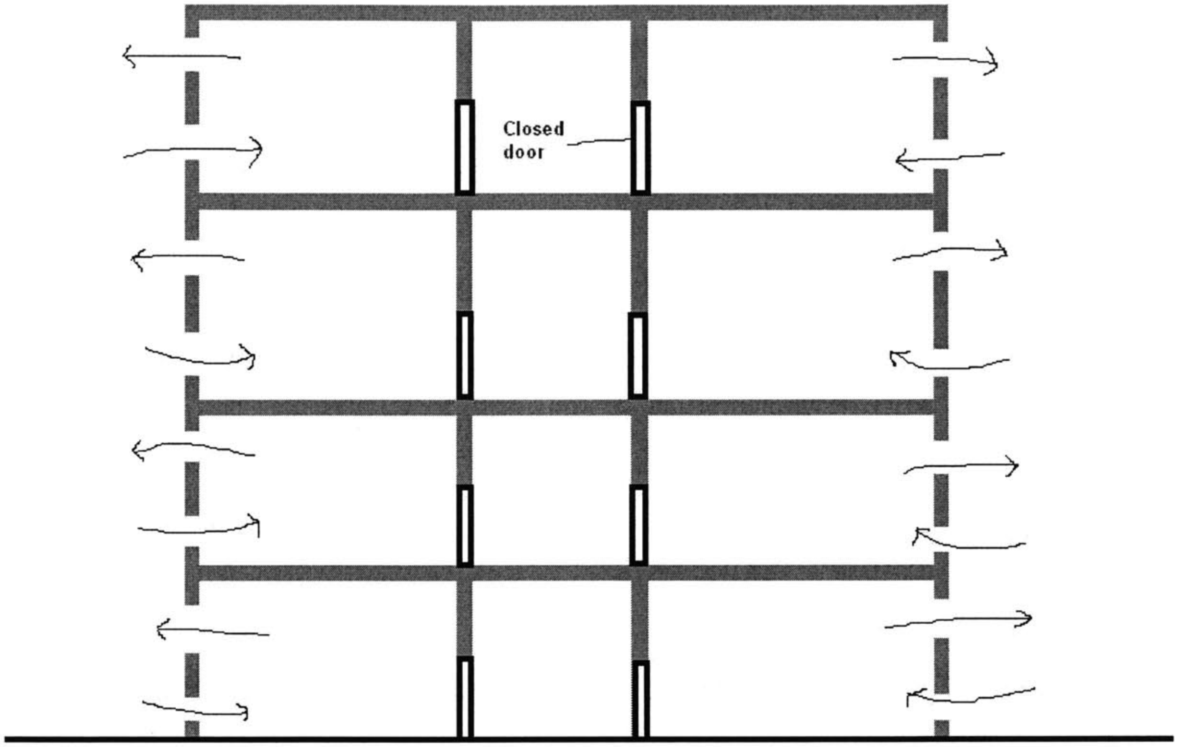


Figure 3 Diagram of single-sided natural ventilation.

1.2.4 Double-skin Façade

In a variety of skyscrapers in Germany, double-skin facades have gained prominence. A double-skin façade, as its name implies, is a façade with two glass layers. The two layers are separated by a gap anywhere from 20 to 120 mm wide. In between the layers, there is typically integrated shading. The shading is designed to heat up due to solar radiation, with the effect of inducing buoyancy driven flow in between the two façade layers; vents on the outer layer allow air to enter and exit. This induced flow takes away most of the heat gain that would otherwise enter into the occupied space. The result is a façade with a very high overall resistive value.

The double-skin façade also allows for natural ventilation. The inner layer can be opened like a normal operable window. Typically, natural ventilation with a single façade is difficult to implement in a skyscraper, because of street noise, rain entry, paper displacement, excessive force on interior doors, and so on. The outer layer reduces the impact of all of these, while still allowing for fresh air to enter the occupied space. The main caveat with using a double-skin is cost.

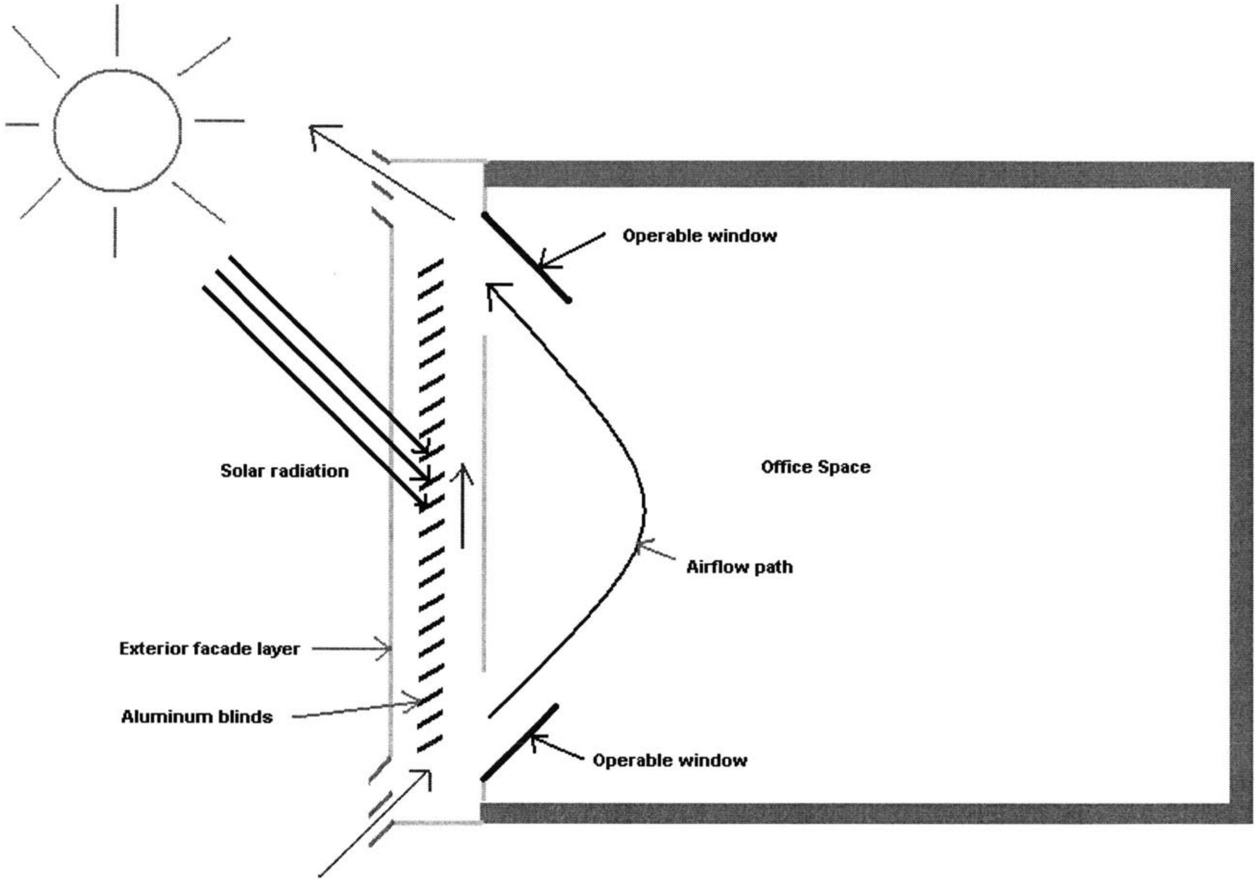


Figure 4 General schematic of double-skin façade.

1.3 Benefits and Disadvantages of Natural Ventilation

On the surface, natural ventilation appears to be a very simple ventilation strategy to implement. At its most basic application, all a building needs for natural ventilation is operable windows. Yet, the scope of this research hopes to cover much more than this simple example. The issues facing the use of natural ventilation are many; they run the gamut of disciplines, including politics, economics, psychology, engineering, and science.

1.3.1 Energy and the Environment

Natural ventilation is seen as a ventilation strategy that has the potential to reduce energy consumption and its associated economic and environmental costs. In the United Kingdom, research has been done on many naturally ventilated buildings to quantify the energy that can be saved in using a passive cooling strategy. Naturally ventilated buildings use between 14 to 41 kWh/m^2 less cooling energy than their air-conditioned counterparts [BRECSU, 2000]. This depends on the particular climate, as well as the level of internal and external heat gains on the building.

In the United States, buildings are often overlooked as a major source of energy consumption and producer of greenhouse gases. In fact, one-third of both of these are a result of the building sector [SBIC, 1999]. Innovation in this sector would go a long way towards maintaining and improving the quality of life for future generations.

There is sometimes confusion over whether using an economizer cycle counts as natural ventilation; it does not. Although the air brought into a building by such a cycle has not been heated or cooled, a significant amount of energy is still necessary to run pumps and fans. An economizer cycle forces outdoor air to run through the standard ductwork used for active mechanical ventilation. This contrasts to the use of fan-assisted natural ventilation. In this case, roof or window ventilators pull or push air through the open spaces of a building. The pressure drop the fans have to contend with is significantly less than the pressure drop encountered in a full-blown duct network. Again, in the United Kingdom, naturally ventilated buildings offset between 20 to 60 kWh/m^2 of annual fan energy consumption used for cooling, compared to their mechanically ventilated counterparts [BRECSU, 2000]. Although individual HVAC components, such as chillers and compressors, are becoming increasingly efficient, lack of space for ductwork make it more and more critical to consider fan energy consumption.

One drawback in using natural ventilation is the lack of heat recovery during the heating season. During the winter, a significant amount of energy can be recovered from heated exhaust air through use of various types of heat exchangers. In a particularly cold climate, most of the energy used will be to heat air. In this case, fan energy consumption becomes a much smaller concern.

In summary, for cooling alone, 10% of a typical commercial building's energy costs can be saved with natural ventilation, while another 15% can be saved by the elimination of fan power consumption, when compared to a building with an all-air system [Kavanaugh, 2000].

1.3.2 Controllability and Reliability

With a mechanical ventilation system, one can assume reliable controllability. An occupant sets a thermostat and a computer or other controller operates the system to achieve a certain ventilation rate, temperature, and in some cases, indoor humidity. With natural ventilation, a greater level of uncertainty exists because of constantly changing outdoor weather conditions. At times, the system may under-ventilate a space, resulting in overheating or poor air quality. At other times, it may over-ventilate the space and result in the need for heating. With natural ventilation, there may also be problems with air distribution. Occupants may feel localized problems with air quality or temperature. With mechanical ventilation, there can be similar problems attaining uniform conditions throughout a building, though.

To many, mechanical ventilation appears to have the upper hand. In many ways it does, but one must also note that although the temperature in a space may be well regulated, air quality may not. Most prevailing ventilation standards are based on a fixed air volume allowance per person, depending on the function of a particular building.

To address the issues of reliability and controllability, advanced automated windows and vents have been developed [Axley, 2001; Windowmaster, 2002], along with predictive whole building control strategies [Knoll & Phaff, 1998] and systems. On a final note though, even with advanced developments, natural ventilation will not work if natural driving forces are not available in the first place. This has led to a trend to adopt fan-assisted natural ventilation or mixed-mode ventilation, where active mechanical ventilation is used as necessary. This trend was particularly visible in many of the buildings discussed in the European tour section of this thesis.

1.3.3 Occupant Comfort

It appears to be the experience of many that mechanical ventilation fails to provide an acceptable environment in many situations [Fisk & Rosenfeld, 1997; Fergus & Kessler, 1998; Oseland, 1998]. In the United States, in particular, many are familiar with working in a cubicle situated in the middle of a large office building, without the view of a window or any natural daylight. Yet, natural ventilation and daylighting has been shown to improve the comfort, health, and productivity of office workers. In comparisons of health of office workers in European buildings of all types, the naturally ventilated buildings reported less prevalence of negative conditions in comparison to mechanically ventilated buildings [Mendell, 1996]. These findings are supported by everyday stories from ordinary people around the world, yet the exact scientific basis for this is not completely certain.

With mechanical ventilation systems, a lot of attention has also been paid to sick-building syndrome (SBS). Indicators of SBS include complaints of symptoms associated with acute discomfort, such as headaches; eye, nose, or throat irritation; dry cough; dry or itchy skin; dizziness and nausea; and fatigue [EPA, 1991]. The cause of the symptoms is not exactly known, although four causes of SBS itself are often cited: inadequate ventilation, chemical contaminants from indoor source, chemical contaminants from outdoor sources, and biological contaminants [EPA, 1991].

Because of the 1973 oil embargo in the United States, national energy conservation measures specified reducing the amount of outdoor air provided for ventilation from 15 cfm to 5 cfm per person [EPA, 1991]. In the late 1980s, these standards were raised back to 15 cfm, when it was found that 5 cfm was not enough to maintain acceptable indoor air quality, health, and occupant comfort. Yet, even 15 cfm may not be enough to counteract the effect of indoor chemical contaminants. These contaminants include volatile organic compounds (VOCs), such as formaldehyde. Adhesives, carpeting, furniture, and cleaning agents emit VOCs. Usually, the levels of VOCs will be highest when a building is first opened, due to the prevalence of new materials.

Another often talked about cause of SBS is the prevalence of biological contaminants in unkempt ductwork. Bacteria, molds, and viruses may breed in stagnant water that has accumulated in ducts and other HVAC components. With natural ventilation, problems such as this can be eliminated. In addition, since all air moving through the building is from the outside, the air change rate achieved with natural ventilation is typically much higher than that achieved with mechanical ventilation. The caveat with natural ventilation is that because air is brought in from outside with no filtration, outdoor air quality levels are still important.

1.3.4 Equipment Requirements

Mechanical heating, ventilating, and air conditioning equipment can account for a significant portion of a building's initial capital costs. In some buildings, these costs can be as high as a third of the construction cost [Chang, 2000]. The potential of reducing a building's construction cost is high with the use of natural ventilation. Equipment can be eliminated or at least sized down.

Equipment costs are not the only consideration. With the complexity of mechanical systems today, space becomes a major issue. Filters, heating and cooling coils, noise attenuators, ducts, heat exchangers, fans, and other components all vie for precious space. For a common commercial building ceiling height of 3.7 m, the combined requirements of fans, vertical distribution, and horizontal distribution systems consume 0.68 to 1.36 m^3 per 3.7 m^3 of useful space in the building; this is equivalent to 18 to 37% of the total volume of the building [Axley, 2001]. By eliminating equipment, buildings can be opened up to provide more natural daylight. In addition, the floor-to-ceiling height can possibly be reduced, for further savings in the cost of building materials or the possibility of the addition of another floor.

1.4 European Natural Ventilation

In August of 2000, a three-week tour of European naturally ventilated commercial buildings was taken. Over twenty-five buildings of various sizes and uses were visited in the following countries: Denmark, Germany, The Netherlands, Belgium, and the United Kingdom. The following criteria were looked at in evaluating each building:

Façade Design – Some buildings feature double-skin facades, while others feature traditional manually operated windows. The goal was to assess how much control a user has over his environment by personal interaction with the façade.

Lighting – In many buildings in the United States, a strong tint is required to control solar heat gain. Because of the reduction in daylight, artificial lighting must be used. On the tour, systems that maximized the use of daylight and minimized the use of artificial lighting were noted with particular interest. The use of daylighting can reduce internal heat loads, increasing the potential effectiveness of natural ventilation.

Building and Systems Layout – The floor layout of a building plays an important role in how well ventilation can work. Buildings can use various types of natural ventilation, as described before: stack, cross, fan-assisted, and single-sided.

Engineering and Architectural Integration – Some architects may not be willing to embrace natural ventilation because of its perceived interference with architectural design freedom. Some buildings visited on the trip showed that natural ventilation can still be effectively incorporated into the design of a building without compromising the integrity of an architects' design style. A growing group of architectural firms are now embracing the challenge of combining form with function.

Shading – Proper shading is a key component in all buildings. Shades from building to building varied in both their style and mounting location, as well as in their control.

Control Systems – Several aspects of building management systems were looked at. They included: temperature setpoints, lighting control, weather monitoring, occupancy sensing, façade, window, and shading control.

Exposed Thermal Mass – Naturally ventilated buildings perform better when there is a sufficient amount of exposed thermal mass such as concrete and brick. These materials can be used to soak up heat during the day and then cooled down during the night, through intensive ventilation. Particular attention was paid to novel approaches of exposing thermal mass.

Cultural and User Perceptions – The success of natural ventilation depends on how willing occupants are to tolerating occasional discomfort due to high temperatures. Interviews focused on finding out how people in a particular region view natural ventilation. Also, information on office building regulations and fire codes was sought after. While technical data provides a good picture of whether a natural ventilation design is successful or not, the satisfaction of the users in a particular building is the ultimate concern.

A table summary of some of the buildings visited in each country is provided as follows:

Name	Location	Cross ventilation	Stack ventilation	Fan assisted natural ventilation	Double-skin facade	Night cooling
Dansk Magisterforening	Copenhagen, Denmark	✓		✓		✓
Roskilde University	Roskilde, Denmark	✓		✓		
Sofiendal School	Copenhagen Suburbs, Denmark			✓		✓
Main Tower	Frankfurt, Germany					
Victoria Insurance Tower	Dusseldorf, Germany				✓	
RWE Tower	Essen, Germany				✓	
Stadttor Dusseldorf	Dusseldorf, Germany				✓	
European Patent Office	Rijswik, Netherlands	✓				✓
Inland Revenue Castle Meadows	Nottingham, England		✓			✓
University of Nottingham Jubilee Campus	Nottingham, England	✓	✓			✓
Queens Building	Leicester, England		✓			✓
Edinburgh Gate	Harlow, England	✓	✓			✓
BRE Environmental Building	Garston, England	✓	✓			✓

Table 1 Summary of naturally ventilated buildings visited in August 2000.

1.4.1 Dansk Magisterforening – Copenhagen, Denmark

The Dansk Magisterforening (Danish Magister Union) is located in Copenhagen. The project is a retrofit of an older building. The architect was Byens Tegnestue and the engineering was done by Wissenberg. The building is a five-floor commercial building featuring cross ventilation as the dominant natural ventilation strategy. The building retrofit was completed in July of 2000. A tour of the building was given by WindowMaster.

The overall building footprint is shallow, making cross ventilation effective. The floor-to-ceiling height is 3.5 meters, higher than in most commercial buildings. Larger, lower windows can be tilt inwards or manually swung open to the side. Smaller, upper windows are motorized and are controlled by the WindowMaster NV control system. Black, motorized, exterior shades provide protection from solar radiation. Exterior windows are tinted light gray to offer further reduction of solar heat gains.

Manually operated transom windows allow flow from one side of the building to the other. Some stack ventilation is possible through three separate stairwells; each with motorized windows and fans near the top. This method of ventilation appears not to be effective due to the small size of the stairwell openings, though.

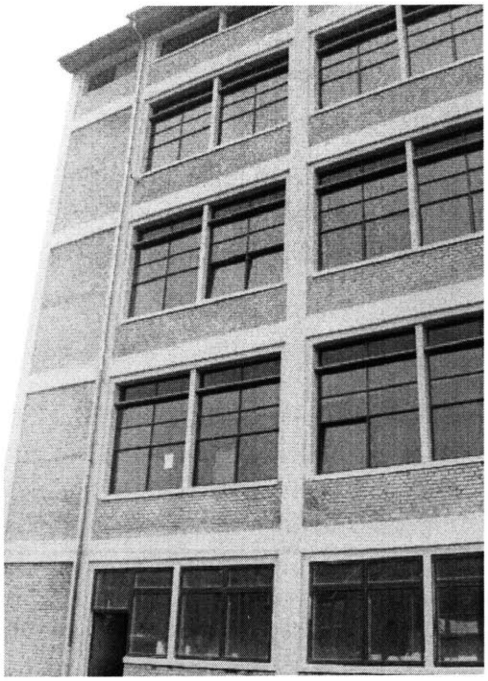


Figure 5 Front façade. Note the tilt windows that are open. The smaller top windows are motorized, while the larger ones are operated manually. The ground floor, which has not been retrofit, is not considered part of the union.

Figure 6 Manually operated transom window. The window allows for cross ventilation through offices and interior corridors. Some objections have been raised over having manual control instead of automatic control for these critical windows. If they are shut, only single-sided ventilation, which is not as effective, is available.

Figure 7 Semi-transparent shading device on exterior. These blinds are motorized. Also, note the motorized windows at the top. Controls for the blinds and windows are located on a panel below the window. The larger manually operated windows can either be tilt inward or opened to the side.

1.4.2 Roskilde University – Copenhagen Suburbs, Denmark

In August of 1998, a new building at Roskilde University was opened. The architect on the project was Henning Larsen, with engineering done by Crone and Koch. A tour of the building was given by WindowMaster.

The building is five stories tall. This fairly large building features fan-assisted stack ventilation, as well as cross ventilation. With stack ventilation, air passes through motor operated windows located in each office, into double-loaded corridors, and then into small atriums spaced throughout the building complex. Fans pull building air through these atriums and subsequently discharge the air to the outside. Small lecture halls feature displacement ventilation. A walk-through of the building revealed fairly stale air, most likely because the ventilation systems were not functioning. Because corridor doors close in the evening for security reasons, stack ventilation through the atriums is not possible during the evening.

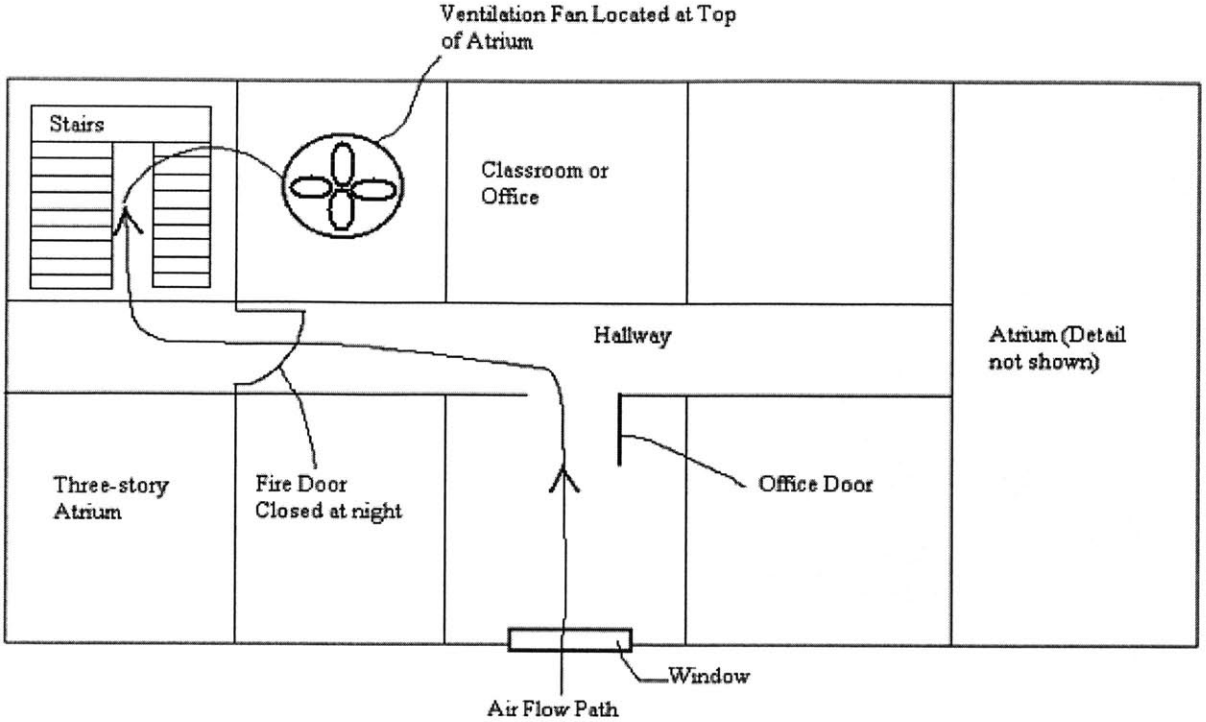


Figure 8 Partial schematic of floor plan. The arrow indicates a typical airflow path. Air is brought through the hallway into three-story atriums. Fans located at the top of each atrium assist the process.

We observed several problems with this building. The main problem is that the exhaust vents in the atriums appear much too small to economically handle the volume flow rate of air required to ventilate each section of the building. The vents were approximately 10 cm in height. Also, although each atrium has a roof skylight that could aid stack ventilation, they are only opened if there is a fire.

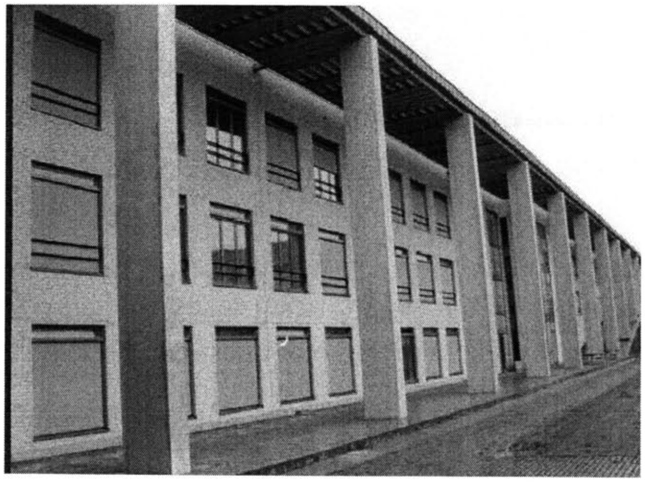


Figure 9 Exterior view. Exterior shading is automatically lowered during non-academic times for security and energy saving reasons. The windows above each shade can be operated by motor.

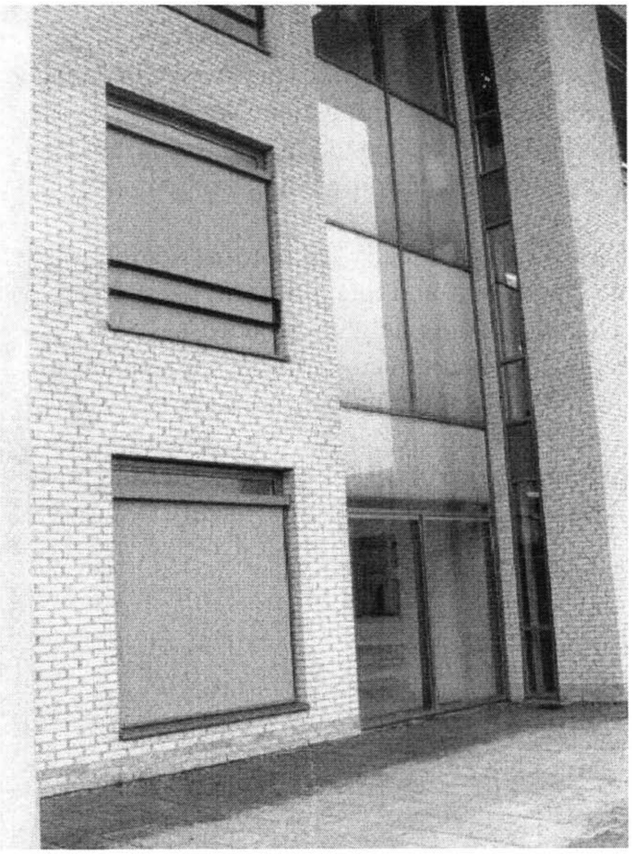


Figure 10 Exterior detail view. The shaded windows open into offices. The airflow path in the building is through the small windows above the shading, through transom windows into the hallway, and then into atriums like the one seen on the right side of the picture.

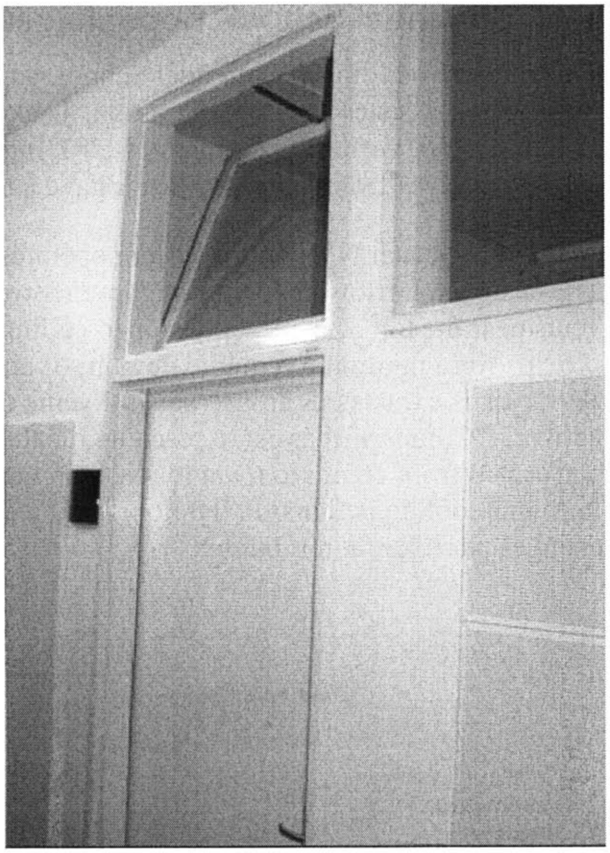


Figure 11 Transom window. These windows allow for airflow movement through interior corridors into three-story atriums. These atriums exhaust air using high-volume fans.

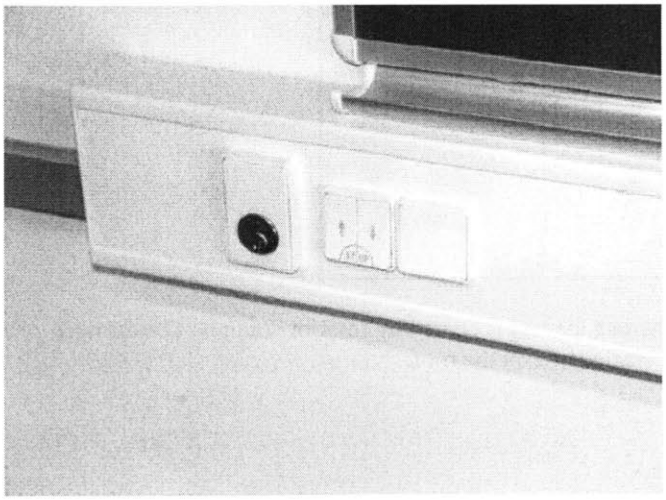


Figure 12 Shading and window controls. These controls were placed on a panel one foot above the ground, making them awkward to use. Also, the building managers made it a requirement that the window buttons be pushed down continuously for operation. Opening the window requires a lengthy one minute of push time.

1.4.3 Sofiendal School- Copenhagen Suburbs, Denmark

This modern building at Sofiendal School, an elementary school several hours from Copenhagen, features fan-assisted natural ventilation. The architect was Raadgiviningstjenesten for skolebbyggeri, with engineering by Leif Lyngkilde. The building opened in August of 2000. Representatives from WindowMaster gave a tour and provided building data.

A WindowMaster NV control system operates windows automatically for optimal ventilation. The designed airflow path is through windows into classrooms and then out through circular vents near the top of the steeply sloped ceilings. The high ceiling height was necessary to provide for a minimum required amount of air changes per hour, even with thirty occupants. Warm air is exhausted through several vents on the roof. When the indoor temperature rises above 24ºC, fans will assist to reach an ideal interior temperature of 22ºC. Night cooling is performed from 10 pm to 6 am to reach an interior temperature of 19ºC. Exposed thermal mass for night cooling is found in the floors and walls. Classrooms receive approximately two air changes per hour, at minimum.

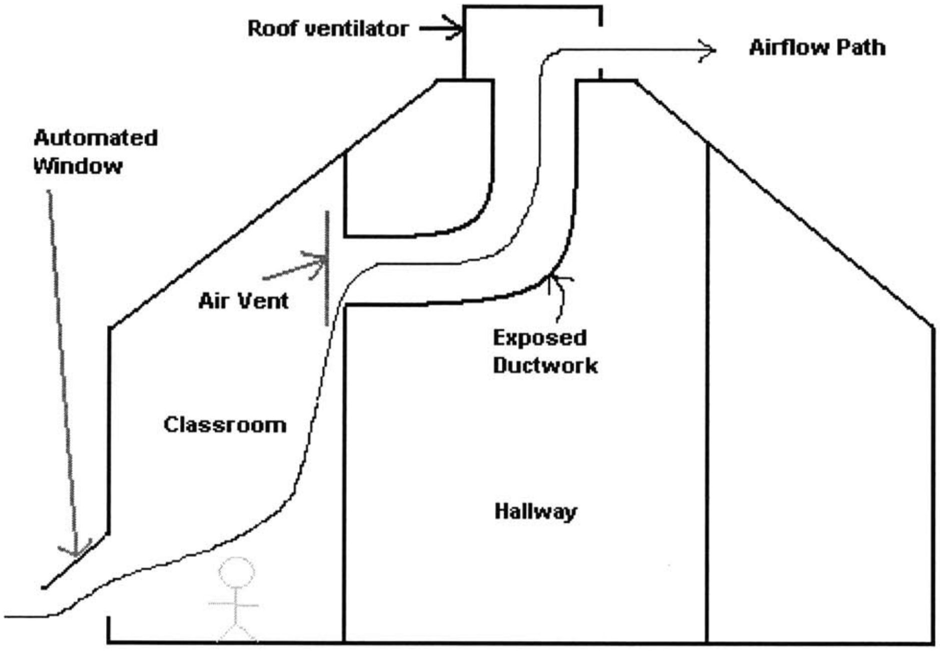


Figure 13 Schematic of airflow path. Air enters from the outside and is heated by interior sources. The air rises towards the ceiling into ducts that run to fan-assisted stacks located on the roof.

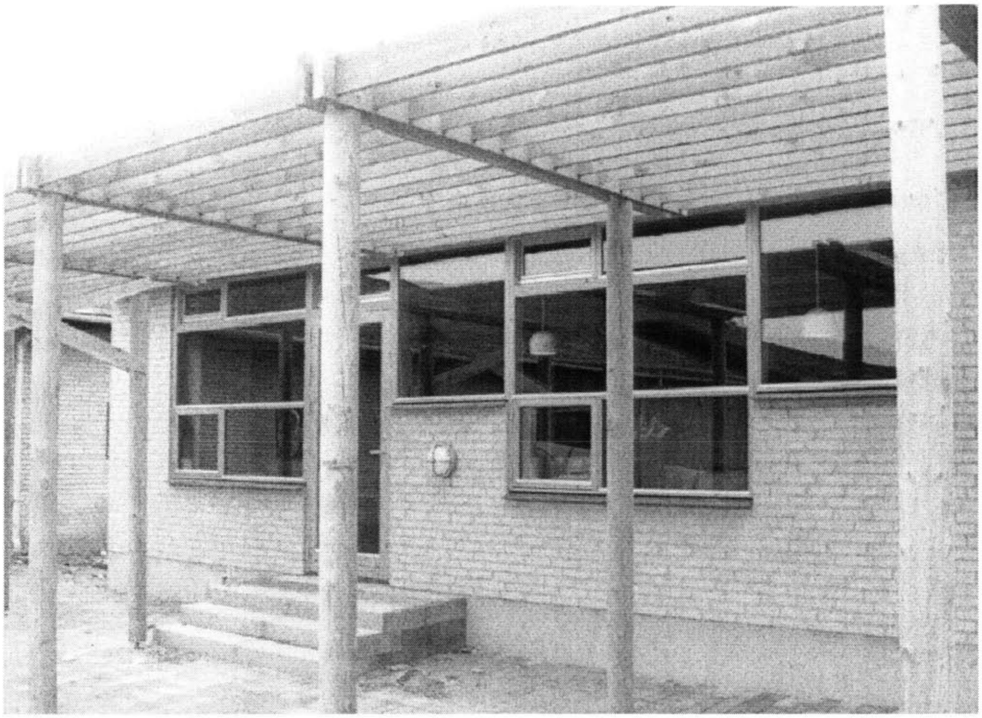


Figure 14 Partial view of building facade. Portions of the façade featuring heavier wood trim are operable windows. Those at the top of the façade are motorized and automatically controlled, while those at the bottom are manually operated. The wooden structure in front serves as a sunshade. In the future, plants may be hung from the structure, for additional shading.

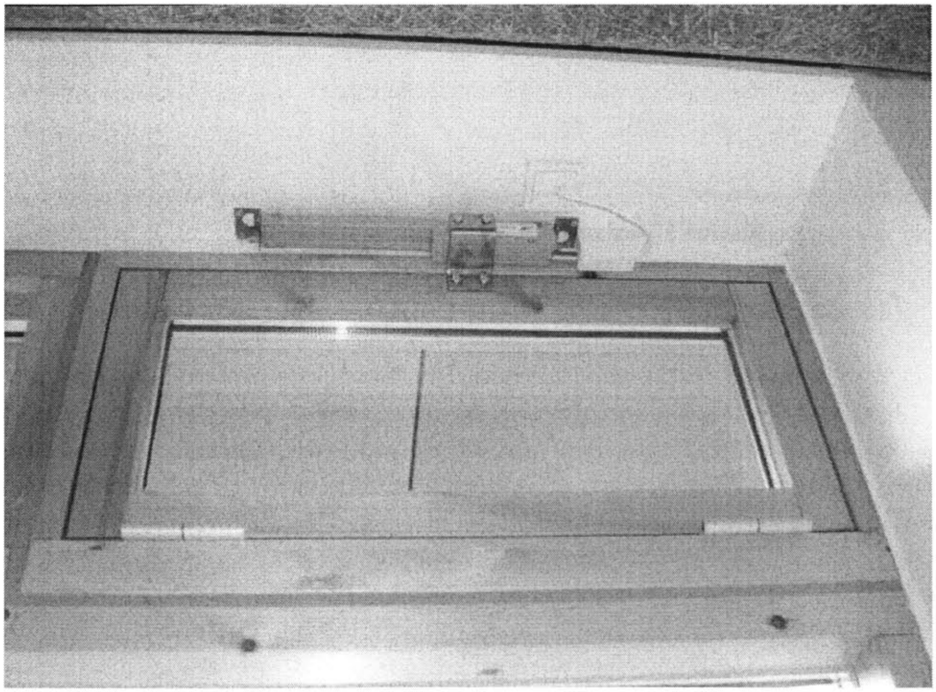


Figure 15 Top-level motorized window. The mechanism consists of a chain that winds out and in. In this case, the designer decided to expose the mechanism to give users a significant visual cue that the window is motorized.

Figure 16 Roof view. Note the ventilation box on the left part of the roof and the weather station on the right. The ventilation shaft exhausts air from vents located in the hallways and in each classroom (see Figure 17). The weather station records wind speed and direction, as well as temperature.

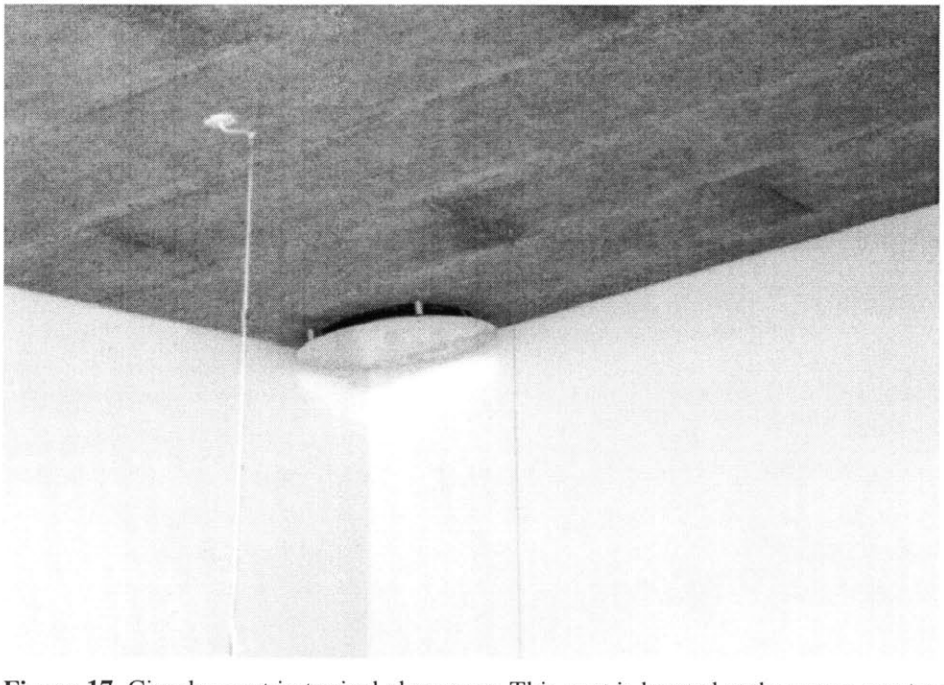


Figure 17 Circular vent in typical classroom. This vent is located at the upper-most portion of a steeply sloped ceiling. The vent feeds into a duct that brings air to one of the ventilation boxes on the roof of the school. It appears that the vent is not configured for optimal airflow. There was likely a trade-off made to make the vent aesthetically pleasing.

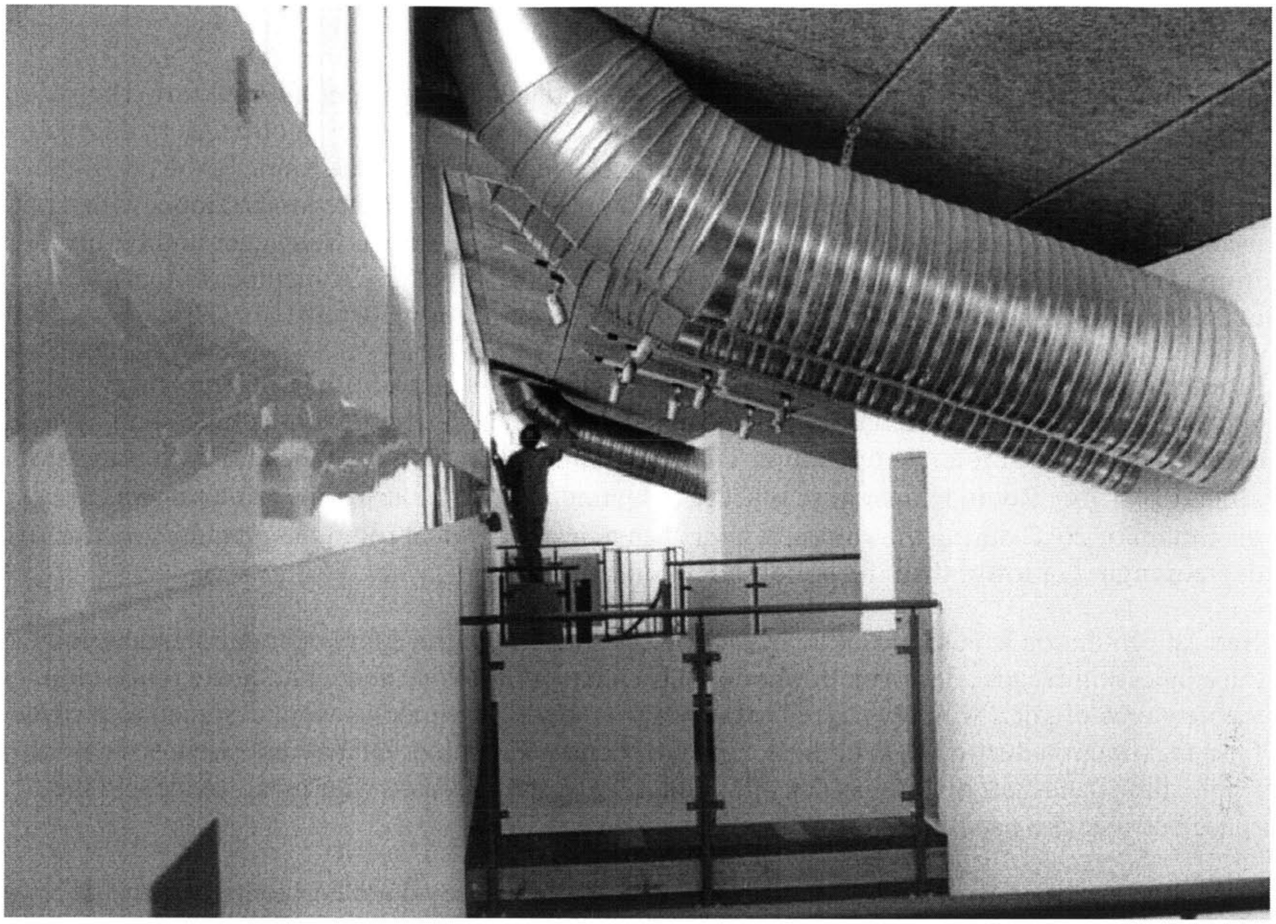


Figure 18 Ventilation ductwork to the roof. Each duct feeds into an individual classroom. Fans in the roof ventilation box assist the process.

1.4.4 Main Tower – Frankfurt, Germany

The Main Tower was opened in November of 1999 and is located in central Frankfurt. The building is occupied by approximately 2,000 employees from companies such as Merrill Lynch, Standards and Poors, Cinven, DLJ, and Merck Finck and Company. The Main Tower, with its height of 200 meters, ranks as the fourth tallest tower in Germany. There are 56 floors with a usable floor area of almost 63,000 m^2. The architect on the project was Schweger und Partner from Hamburg. Josef Gartner and Co designed the building envelope. A member of the marketing staff for the Main Tower gave a tour, as well engineering details.

Literature on the Main Tower emphasizes the availability of air-conditioning. Mechanical ventilation provides a minimum of two and a half air changes per hour, while chilled and heated ceilings help control room temperature. Typically, the water run through the chilled ceilings is around 14-15°C. Room temperature is set to a minimum of 21°C during the winter and a maximum of 26°C during the summer. Users can adjust individual room temperatures up to two degrees higher or lower than the building setpoint.

Natural ventilation is possible at the Main Tower using one of the 2,550 operable windows on the single-skin facade. Based on promotional literature, it took one and a half years to develop the new type of glass windows used for the Main Tower. The windows were designed to provide for a maximum reduction in solar heat gain and sound penetration. Each window consists of two single glass panes, each 10 mm thick. Two sides are vacuum-coated with metal-oxide and the space between the panes is filled with inert krypton gas.

Typically, one operable window is available in each office. They open horizontally (parallel to the building façade) up to 20 cm and are automatically closed with the onset of rain or high winds (>70 km/h). Closing time from the fully open position takes approximately two minutes. One and three-eighth inch aluminum blinds, which are mounted on the interior, automatically adjust to provide shading when there is a significant amount of solar radiation.

Lighting is provided by a combination of daylight and artificial lighting. Artificial lighting can be switched on and off manually, but are usually controlled automatically by the BMS depending on the amount of daylight in a particular room. When the amount of daylight has reached a certain level, the row of ceiling lamps nearest the windows are completely switched off.

Overall, occupants at Main Tower take advantage of the availability of natural ventilation. Based on personal observations though, the high noise level of the window actuators would be a distraction to some and could reduce some occupants' use of natural ventilation. In general, it appears that air-conditioning still dominates ventilation practices at Main Tower, although it is encouraging to see natural ventilation usage in a fairly tall modern skyscraper, without the use of a double-skin façade.

Figure 19 Exterior view. At the time this picture was taken, rain had just started falling. Note that almost all windows are closed, with the exception of some, which were in the process of closing.

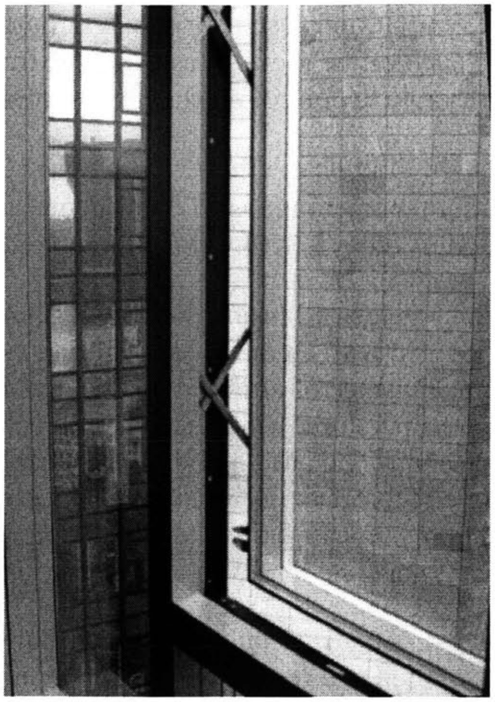


Figure 20 Operable window. This is a representative view of one of the 2,550 operable windows of the Main Tower. The motors actuating the scissors linkage are fairly noisy.

1.4.5 Victoria Insurance Tower- Dusseldorf, Germany

Victoria Insurance, one of Germany's largest insurance companies, opened a new 28-story naturally ventilated tower during the summer of 1998. The tower is located at a meeting point of three parks in Dusseldorf: the Rheinpark, the Golzheimer Cemetery, and the Ehrenhof. These three parks meet at Victoriaplatz, the location of a growing Victoria Insurance building complex. The architectural firm was HPP Hentric-Petschinigg and Partner. The building envelope was designed and manufactured by Josef Gartner and Co. The building manager for the Victoria Tower complex gave a tour, as well as technical details.

The Victoria Tower has a diameter of 34.4 m and measures 108.8 m in height. There is total of about 52,000 m^2 of usable floor space. It is a dominant sight in Dusseldorf, the federal capital city of the North Rhine Westphalia. The Victoria Tower features several energy saving devices, including a double-skin façade. The façade consists of an interior hinged and tilted window façade with insulated glass, and a second, exterior glass skin. The gap between the two layers is 30 cm. Each pane of glass in the double-skin has a thickness of 8 mm. Air is brought into the air channel through two and three-eighth inch diameter holes set half an inch apart in V-channels located along the sides of the windows. Air exits through horizontal slats near the top of each window element. Natural ventilation in the offices in the tower is supplemented by mechanical ventilation during high temperature periods or on windy days when windows cannot be fully opened or must be closed. A wind station inputs into the BMS which will signal an audible warning in rooms where windows should be closed due to high wind pressure.

When mechanical ventilation is used, air enters through outlets located underneath storage cabinets located in each office room. Waste air is extracted through vents located above the cabinets. The user is able to control mechanical ventilation individually.

Cooled water, brought through overhead ceiling pipes, is used when temperatures rise above 26°C. The target room temperature is 21°C. When heating is in operation, the temperature in each room can be adjusted to ± 3°C of the building setpoint.

Sun protection, which is located inside the double-skin façade, consists of flexible, perforated aluminum slats. Coupled with an intelligent lighting system, the blinds are automatically aligned to provide an optimal balance of artificial and natural daylight. A weather station measures parameters such as temperature, wind speed and direction, and light intensity. The entire tower runs on a computer-controlled and freely programmable building transmission engineering system using European Instabus (EIB) technology. Roughly 25,000 EIB components in the tower are controlled using this bus. Lighting, heating, cooling, blinds, and power outlets in individual offices are switched to operate based on actual interior and exterior conditions.

Energy is generated on-site using three natural gas turbines. Heat from computers and other high output devices is captured and reused for heating in other areas of the building. Energy consumption in an older Victoria Insurance building is about 400 kW/m^2 per year while energy consumption in the new tower has been about 170 kW/m^2 per year. The tower released 16,000 tons less CO_2 annually, compared with a typical European office building of similar square footage.

Based on personal observations, the building appears to function well. The building appears to provide a significant amount of daylight and fresh air to its occupants, which in turn appears to have created a very hospitable working environment. The Victoria Tower is expected to save energy costs ranging into eight figures over a ten year span, which should give more investors incentive to consider ecologically-minded alternatives in new building construction.

Figure 21 Exterior view. At the top is a panel featuring photovoltaic cells. *Picture Courtesy of Victoria Insurance.*

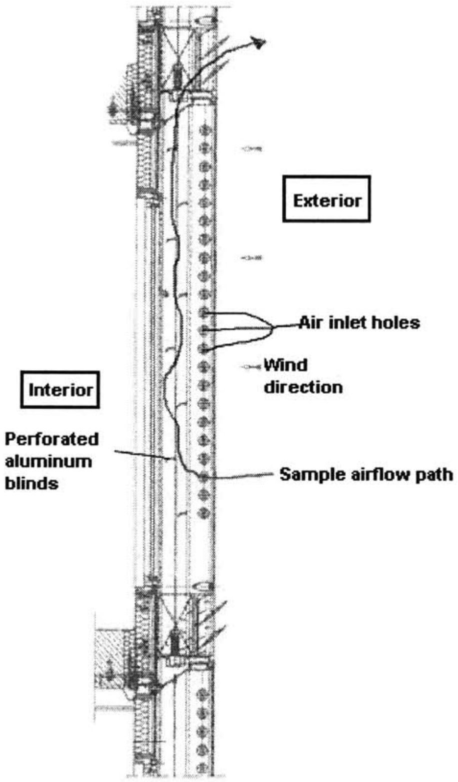


Figure 22 Side-profile of double-skin. Note that air enters through holes along the side of each window. Exhaust air exits past louvers at the top of each window. *Diagram Courtesy of Victoria Insurance.*

Figure 23 Exterior view of double-skin. Note the V-Channel; the holes are where air enters the double-skin.

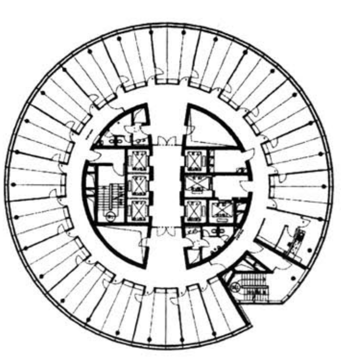


Figure 24 Sample floor plan. All offices have windows to the exterior. The interior core houses elevators, storage rooms, and mechanical plant equipment.

Figure 25 Partial view of façade. Note that interior windows can be tilt inwards or opened to the side. Inlet is through the channels separating each component of the façade.

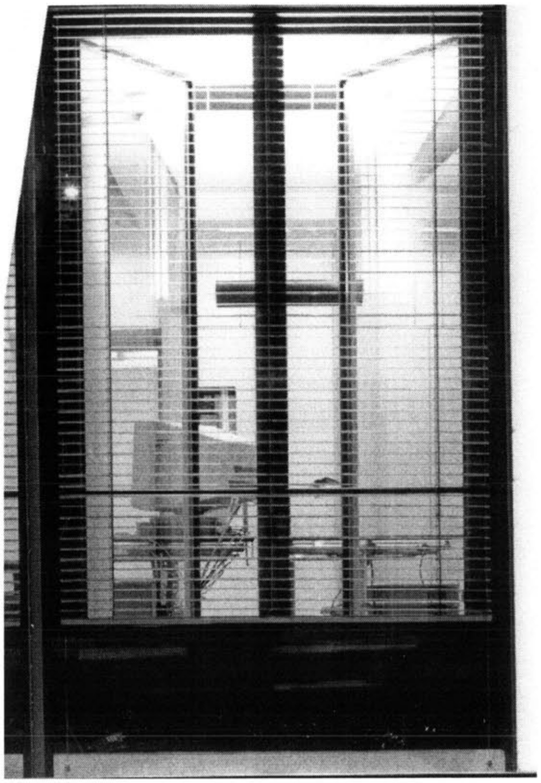


Figure 26 Example of the transparency of the façade. The use of a double-skin permits the use of non-coated glass, without severe penalties in solar gain. The shading system is located in the space between the two layers of the double-skin. *Photo Courtesy of Victoria Insurance.*

1.4.6 RWE – Essen, Germany

The RWE tower is the home of primarily, mid- and upper-level management of RWE, one of Germany's largest power companies. The 120 meter tall circular tower was designed by Ingenhoven, Overdiek, und Partner and built at a cost of approximately 150 million US dollars. Ingenhoven was selected to design the tower as a result of an intense competition to create an environmentally friendly high-rise. During the RWE competition, Ingenhoven's firm had a simultaneous entry in the Commerzbank tower competition. Norman Foster's firm won the Commerzbank competition (Ingenhoven's firm came in second place), but the RWE tower was completed first, earning it the right to be called the first ecological high-rise in Europe. The tower was ready for occupancy in March of 1997. There are 31 floors with a usable floor area of 20,000 m^2. A tour, as well as technical data, was given by architects from Ingenhoven, Overdiek, und Partner.

Upon entering the tower, visitors are greeted by a three-story lobby that features a significant amount of exposed structural concrete. Heating in the lobby occurs at the base of the windows, while fresh air is directed through vents aimed directly at the windows, rather than into the interior space. The vents are incorporated in the façade frame.

The RWE tower, the fifth highest building in Germany, features a double-skin façade engineered by the Gartner Company. The top-level conference room is fully air-conditioned using a displacement ventilation system. Source air is channeled through perforations in the metal floor and then through a loose-mesh carpet. Exhaust vents are located at the top of the room, surrounding a large skylight. The upper five levels of the tower are reserved for upper-level management.

The BMS controls lighting and ventilation. When windows are open, all systems are shut off. When windows are closed, air conditioning is available through the use of chilled ceilings. When wind speeds are in excess of 8 m/s, an audible warning to close the windows is issued in each office. During the summer, the maximum temperature allowed is 27°C. During the winter, heating can be controlled in each room to ± 3°C around the building set point. The blinds, located in the channel of the double-skin façade, are lowered automatically during inclement weather.

Creating as transparent a building as possible was based on a desire to use daylight as much as possible in order to increase the quality of the working environment. A critical requirement of using daylight is to have very transparent glazing. In addition to daylighting, RWE specified that natural ventilation was to be used. Having operable windows in a modern skyscraper, at the time, was unprecedented. A third demand was to provide occupants with adequate sun protection without using interior-mounted devices.

The demands specified were fulfilled, without compromise, by using a double skin façade with a 50 cm wide airflow gap. The exterior wall of the RWE tower is made of flint glass that is fastened in eight locations; specialists from Gartner note that the exterior wall is effectively invisible from the interior. In the façade channel, metal panels in the shape of a fish mouth form a transition from the inner to outer glass surfaces. Window cleaners can raise the top flap of the fish mouth to reach a flat walking platform.

The inlet and outlet vents on the façade include louvers designed to prevent rain infiltration without the use of electronically controlled flaps. Arranging the inlet and outlet vents on top of each other was decided to be unacceptable because exhaust air would take the shortest path up to the floor above and enter it in the place of fresh environmental air. If this happened, air quality would decrease with every subsequent floor. Another concept was to have air flow from the bottom to the top of the façade; this was found to also be problematic. The final solution was to create diagonal air streams in the façade cavity. This required that supply and extract air vents be placed next to each other. This was achieved by alternately perforating the bottom and topsides of the double-paneled fish mouth platforms connecting the inner and outer glass walls. The final vent width was 120 mm.

The slatted blinds in the façade corridor have virtually the same effect as exterior sun shading. The slats absorb solar radiation, which in turn causes them to heat up. The secondary heat transmitted by the slats remains within the infrared spectrum and is primarily deflected by the interior layer of glass. The exterior glass layer protects the blinds from wind, humidity, and other weather.

Various aspects were considered in the ventilation design of the RWE tower. They included: natural ventilation in windy conditions, natural stack ventilation of the entire building, ventilation in the double-skin façade, ventilation of the elevator tower, and natural ventilation of the ventilation duct network [Briegleb, 2000].

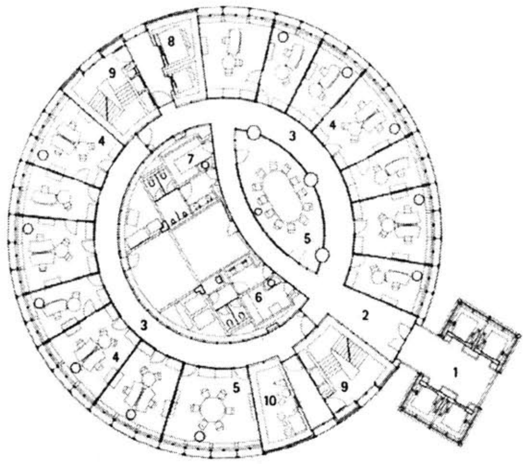
Based on the RWE guidebook [Briegleb, 2000], it was found that cross ventilation at medium wind speeds would produce up to a 40-fold air change rate. Thus, the double-skin façade reduces cross-ventilation sufficiently to prevent papers from flying around, as long as outside wind speeds were not in excess of 8 m/s. At that speed, there is around a 200-fold air change rate. Using past weather data, it was found that the double-skin façade would be able to reduce door opening forces to levels around 40-60 N for the majority of the time.

Because of the stack effect in stairwells and the elevator shafts, special attention was paid to where certain air locks and vents should be placed throughout the building. Through extensive wind tunnel and computer modeling, a design consensus was reached that would allow natural ventilation to be used as long as outside wind speeds did not reach an excess of 8 m/s (300 hours per year) or a temperature below 2°C (100-250 hours per year) [Briegleb, 2000].

Based on personal observations, the RWE tower is an example of very bold and forward thinking. It appears that Gartner Company, the façade designers, as well as Ingenhoven, Overdiek, und Partner were very concerned with setting a good example for others to follow. It was also good to see that an energy company was visionary enough to specify that natural ventilation be used to reduce energy consumption and improve worker comfort. It was interesting to hear that security for this building is very tight, due to the fear of damage from environmental groups. Some groups have put up negative banners on the building site; perhaps without knowledge that the RWE tower has sparked a movement to the construction of greener skyscrapers. On a flip side, the RWE tower did not come to existence cheaply. Other companies may not be willing to erect high-rise towers with advanced facades, both due to their high cost, as well as the fact that very detailed analysis of airflow patterns must be performed. It will be necessary to find a compromise between the elegant façade design at RWE and something as effective, yet cheaper to design and manufacture.

Figure 27 through Figure 36 are courtesy of Ingenhoven, Overdiek, und Partner. They are taken from the book, *High-rise RWE AG Essen* [Briegleb, 2000].

Figure 27 Exterior view at night. The rectangular shaft on the left of the circular portion of the tower houses 4 elevators for best use of space.



Typical floor (M 1:320)

1	Elevator lobby	6	Catering service room
2	Access corridor	7	Kitchette
3	Circular floor	8	Fire brigade elevator
4	Office	9	Emergency stairs
5	Conference	10	Technical installations

Figure 28 Typical floor plan. The core of each floor consists of a conference room, bathroom facilities, storage, and a ventilation shaft.

Figure 27 Exterior view at night. The rectangular shaft on the left of the circular portion of the tower houses 4 elevators for best use of space.

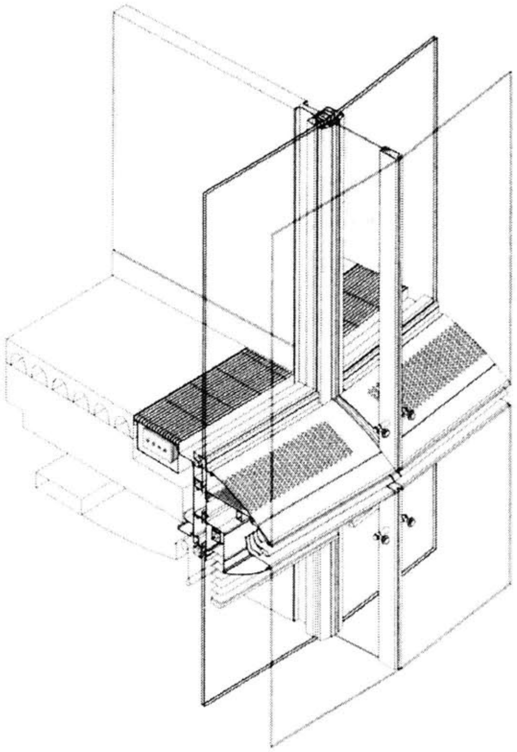


Figure 29 Isometric view of façade element.

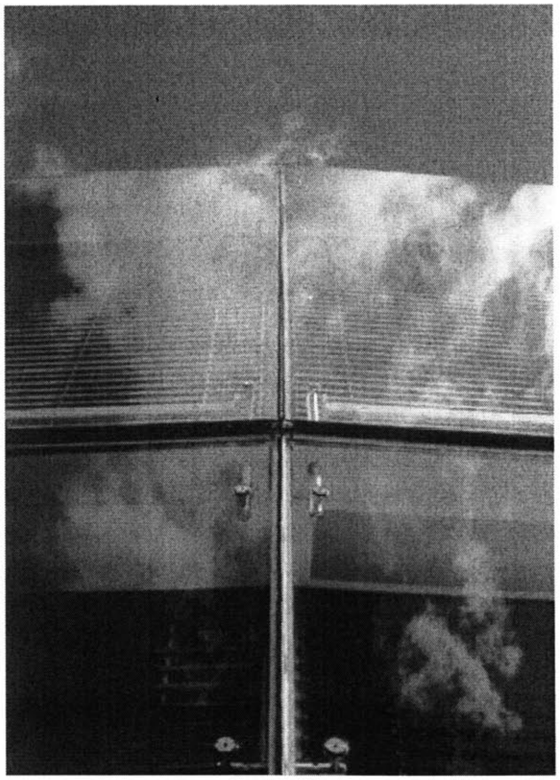


Figure 30 Actual view of façade element. From afar, the RWE tower appears to be a perfect circle, yet it is actually a 50-side polygon. The minimalist glass mounts allow for a unobstructed and complete floor to ceiling view in each room.

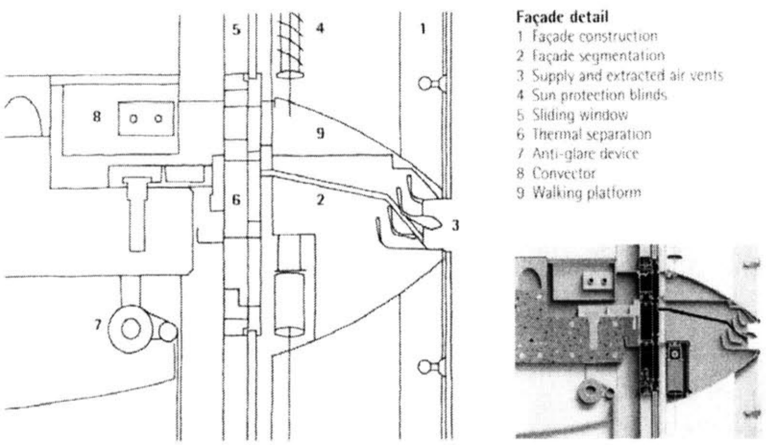


Figure 31 Cross-section view of "Fish-Mouth" façade assembly. While the apparatus appears complicated, this method of packaging components is carefully designed. All components are carefully integrated to provide the maximum amount of unblocked view to the outside as possible.

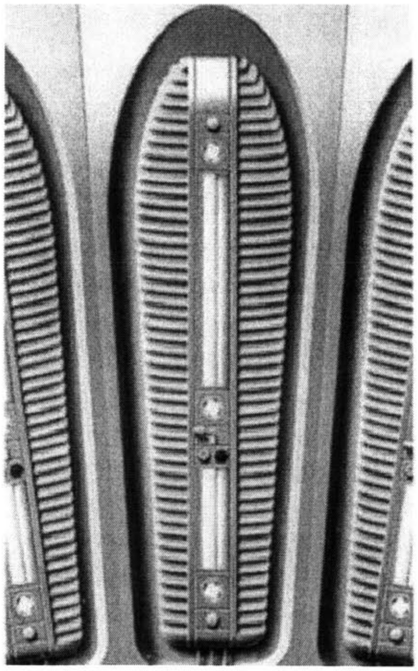


Figure 32 "Surfboard" chilled ceiling. Ingenhoven came up with the concept of a surfboard shaped set of heat exchanger fins. It was found that this would provide optimal temperature control using a fairly compact design.

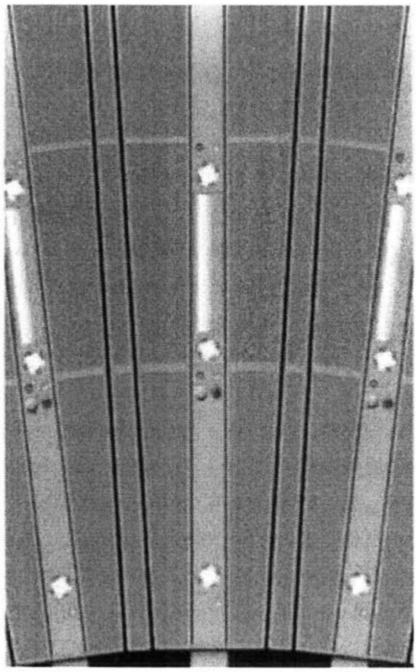


Figure 33 Final ceiling covering.

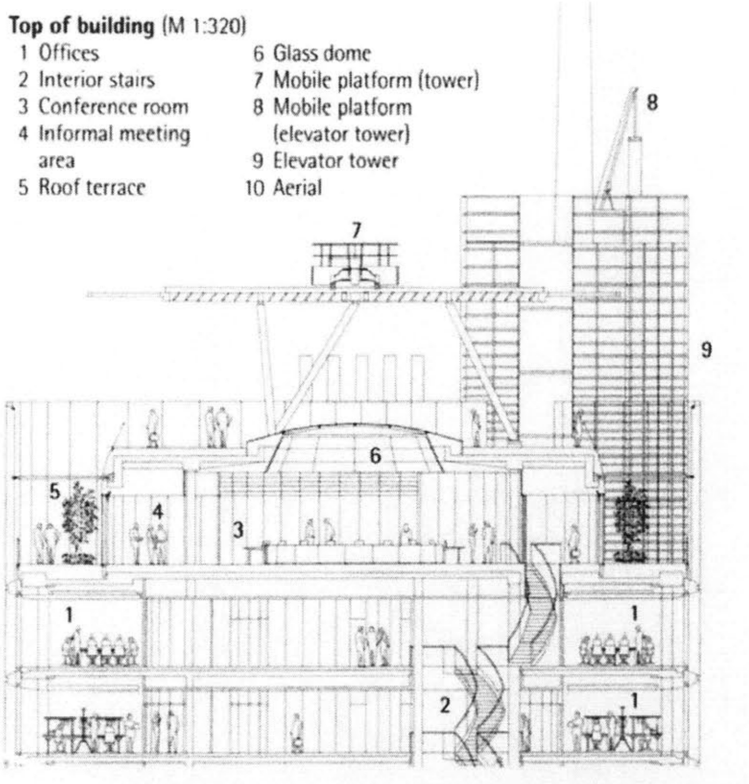
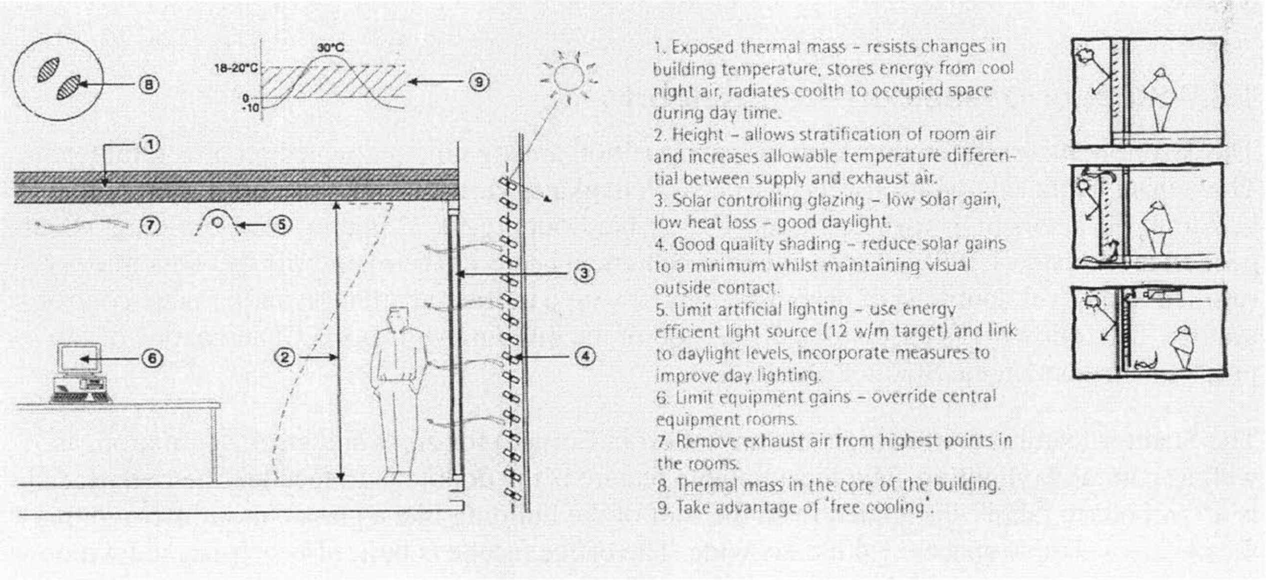


Figure 34 Schematic of top five floors. Note that curving stairs allow transit from floor to floor with ease. Fire codes were met by using special glass fire doors for zoning. The façade of the building continues to the top two floors. There is no roof over the outer ring of the upper two floors, thus creating an open-air garden space.



1. Exposed thermal mass - resists changes in building temperature, stores energy from cool night air, radiates coolth to occupied space during day time.
2. Height - allows stratification of room air and increases allowable temperature differential between supply and exhaust air.
3. Solar controlling glazing - low solar gain, low heat loss - good daylight.
4. Good quality shading - reduce solar gains to a minimum whilst maintaining visual outside contact.
5. Limit artificial lighting - use energy efficient light source (12 w/m target) and link to daylight levels, incorporate measures to improve day lighting.
6. Limit equipment gains - override central equipment rooms.
7. Remove exhaust air from highest points in the rooms.
8. Thermal mass in the core of the building.
9. Take advantage of 'free cooling'.

Figure 35 General engineering requirements specified during the design phase. All requirements were met in the final design.

To evaluate the effectiveness of the design, monitoring data was taken on the building over a period of six months beginning in January of 2000. According to Mr. Canessa, the overall energy consumption has been less than expected, while the ability to control climate has turned out to be better than expected. A complete assessment of the performance of the building is not possible because the summer climate up to the year 2000, was fairly moderate.

Due to legal reasons, there was a two-year delay in the construction of the Stadttor. This delay time was used to perform additional supercomputer and wind tunnel modeling. The first phase, which took seven months, increased the efficiency of the façade by 300-400% over the original design. Upon intuition, it would appear that the larger the opening from the outside into the double-skin cavity, the better the airflow; this turned out to be false. With simulation on a simple design using an opening of 70 cm, it turned out that only 10% of the air would actually pass through the channel; the rest would get caught up in vortices near the entrance. Adding louvers increased efficiency to 60%. After more refined analysis on exactly what shape and location the louvers should have, the efficiency was brought up to 80%. A third iteration did not provide any significant gains. The final airflow gap distance was 1.4 meters. This wide gap was chosen to give occupants the ability to walk inside the double-skin cavity for leisure and recreation.

Finding a designer for the façade was not an easy process. EngelCanessa, the project management team, tried out two different engineering firms before settling on DS Plan. Wind channel tests were performed in Aachen, Germany using a process similar to designing an airfoil.

One design element in the Stadttor is ceiling cooling using copper tubes. The goal is to keep occupants with cool heads, but warm feet. Water cooled to 1°C by a large underground pipe system is used in the copper tubing. Mr. Canessa emphasized that water is a much better medium for cooling than air (typically 10-12 times more efficient) and avoids many of the hygiene issues associated with air-to-air cooling. Using ground-cooled water to cool the building eliminates the need for using gases of fossil fuels; water pumps are the only major equipment requirement.

The building is zoned by floor. Using the BMS, the climate for each floor is automatically controlled. Two and a half air changes per hour is the target minimum requirement at the Stadttor. When the temperature drops below 5°C, the façade is closed. Mechanical ventilation is used when the outside temperature reaches 23-24°C. Individual controls in each room allow the user to go ± 3°C of the zone set point, in theory. In practice, it is difficult to attain such a range because occupants usually keep their doors open, allowing the passage of air throughout an entire floor. Sometimes a 2°C change is possible, but any more than that is not feasible. For reference, the human body typically cannot sense a change of 1-1.5°C.

Heating of the building is accomplished using floor radiators. They use excess steam from a power plant located in Dusseldorf. Dehumidification during the summer months is done using a desiccant wheel.

The shading system, located inside the inner double-glazing skin, is controlled by the BMS. Aluminum blinds will go down when the sun has been out for longer than 10 minutes and will rise when the sun has been behind clouds for more than 10 minutes. Individuals can control the blinds using an electronic control pad located in each room. Input to the system is from a weather station on the roof, which measures wind direction, wind speed, light intensity and direction, and

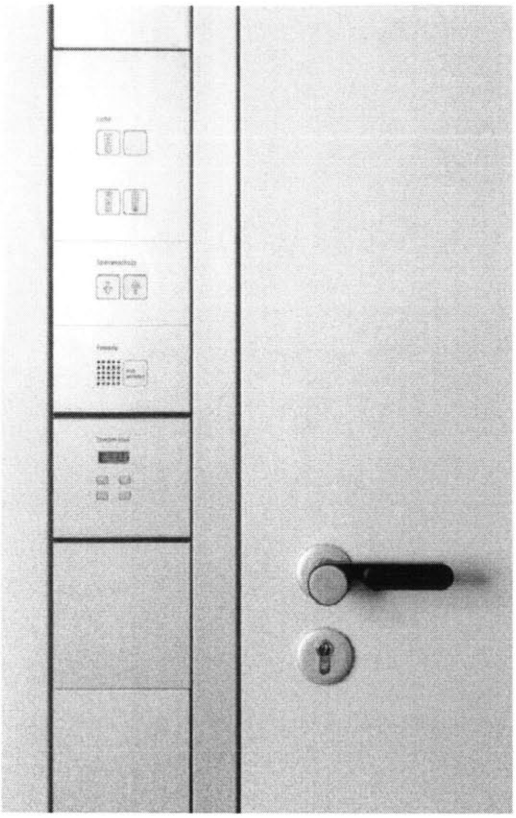


Figure 36 Individual office control panel. The panel provides lighting and shade control. An audio and visual warning is given when the façade must be closed due to high wind pressures.

Figure 37 Roof-top weather station.

1.4.7 Stadttor Dusseldorf – Dusseldorf

The Stadttor Dusseldorf is the result of a competition among nine renowned architectural teams. The winner of the competition was Overdiek, Petzinka & Partners. The result is a rhomboidal building, 75 meters high with 16 floors. The usable floor area is 27,000 m^2. The building, which opened in January of 1998, was designed with human needs as the main priority. This priority resulted in a novel double-skin design integrated with a unified ventilation and climate control system. The following is based on a discussion of the building with Boris Canessa, one of the project managers on the Stadttor Dusseldorf.

The Stadttor features a 56 m high atrium (tallest in Europe) for cross and stack ventilation, as well as natural daylighting. The most notable feature is the double-skin façade. The outer façade is a "secondary "skin" suspended from the roof of the building like a glass curtain. Behind this façade are walkable spaces, 1.4 meters wide. The office façade is built of beech-framed windows featuring a heat-protective glazing going from floor-to-ceiling. It is interesting to note that the busiest highway in Dusseldorf runs *underneath* the building, a potentially potent pollution source.

temperature. There are also eight temperature sensors on each façade, as well as four wind speed sensors located in the atrium. The top three floors, currently rented out by the Boston Consulting Firm, take up 21% of useable space (2200 m^2 each floor) in the Stadttor. The remaining floors feature 1,600 m^2 of usable space per floor. Rent in the year 2000 was approximately $68-76 US per square meter per month.

Based on personal observations, the Stadttor Dusseldorf is yet another example of a building designed with very forward thinking. What is most notable about the building is the large width of the double skin façade gap. Because airflow through the façade is unrestricted from top to bottom, it appears that there may be issues regarding air quality and noise. In fact, during the visit, it was sometimes possible to hear sounds from other offices traveling down the double-skin gap. All in all though, the building is remarkable architecturally and appears to use natural ventilation effectively. The building was presented in 1998 with the MIPIM Award for best office building and a Jury Prize for best building in general.

Figure 38 Exterior view. Note the atrium in the center. The top three floors are served by a smaller atrium. Windows at the bottom and top of the larger atrium façade allow for stack ventilation.

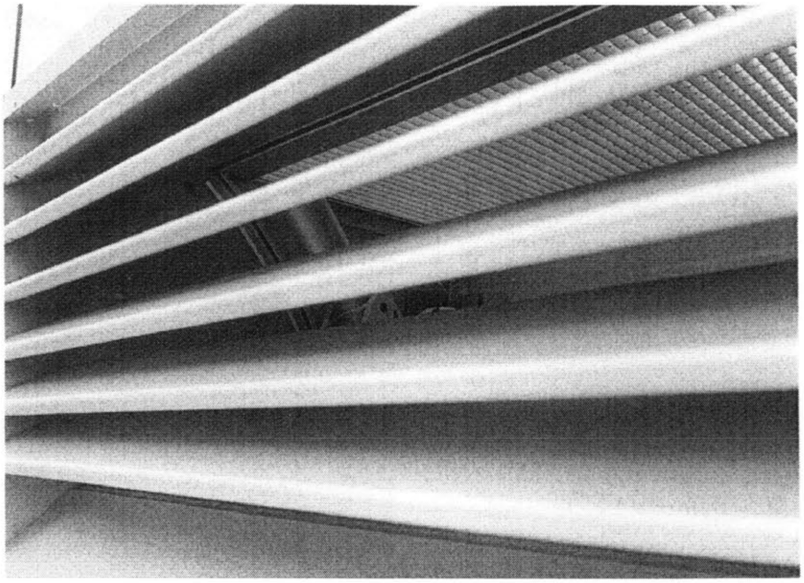


Figure 39 Inlet louvers to the double-skin cavity. The grill behind the louvers serves as a walking platform. Air is directed upwards through this platform. *Photo Courtesy of EngelCanessa (http://www.stadttor.de).*

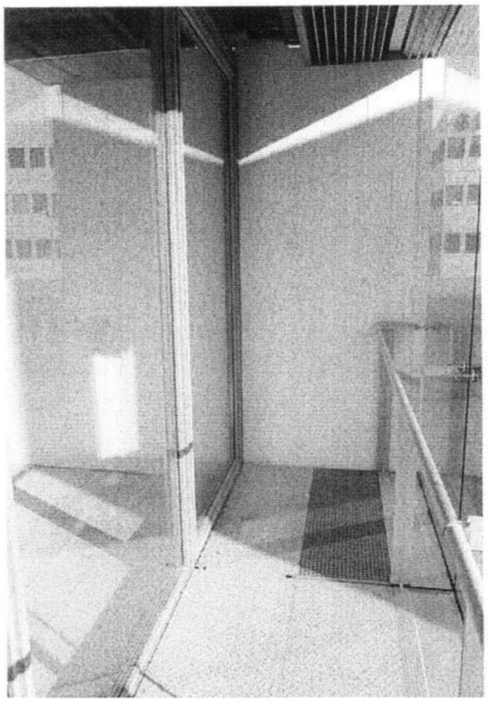


Figure 40 Double-skin cavity. This particular double-skin design has a gap significantly larger than those of other double-skin buildings. The gap is sometimes used as a walkway to travel from office to office. *Photo courtesy of EngelCanessa (http://www.stadttor.de).*

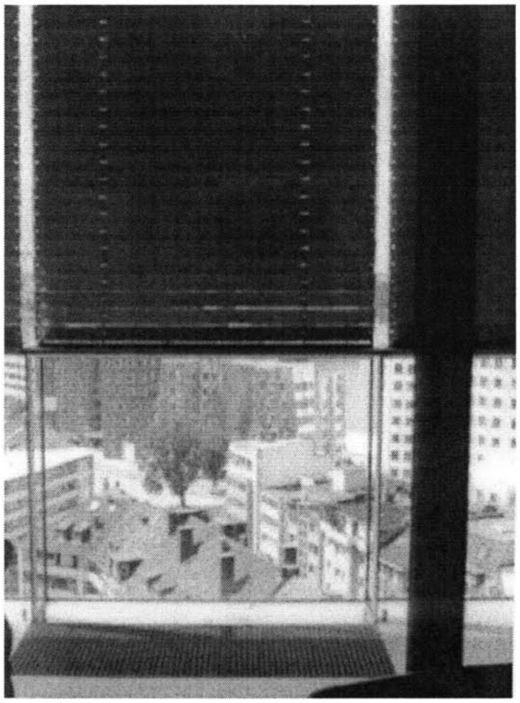


Figure 41 View of double-skin façade from the inside of a typical office.

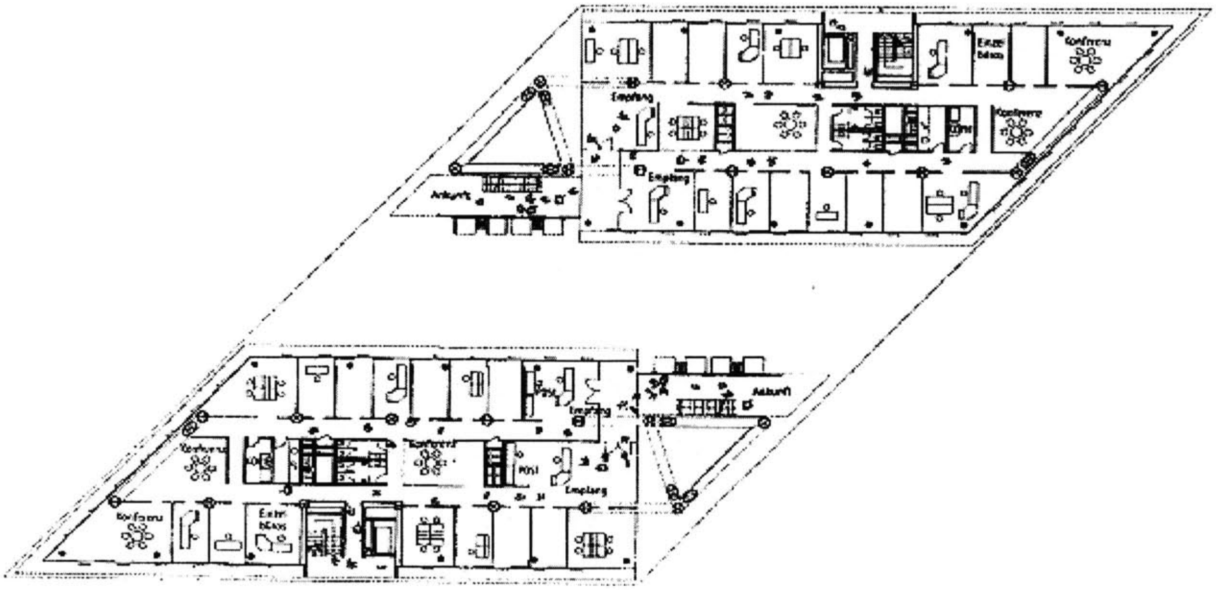


Figure 42 Typical floor layout for levels 1-13. The atrium in the center provides ventilation to those offices adjacent to it. All offices receive daylight and fresh air. (http://www.stadttor.de)

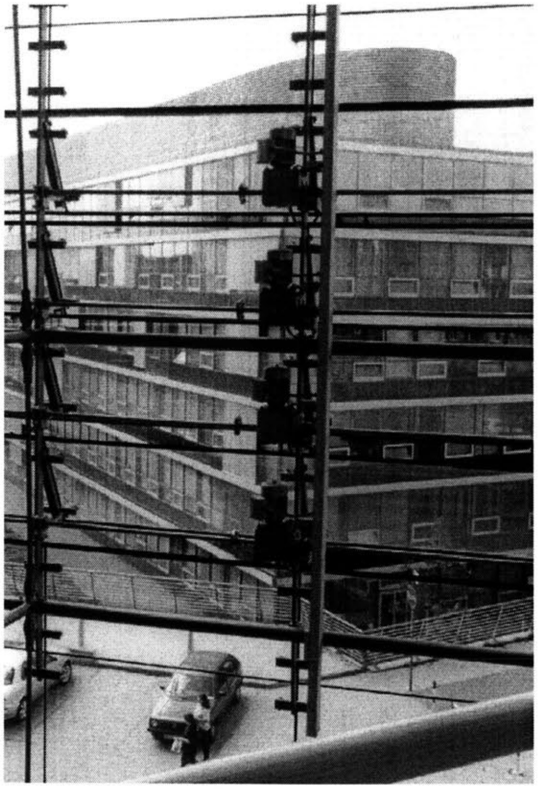


Figure 43 Lower motorized atrium windows. A similar set of windows is located at the upper portion of the atrium facades.

1.4.8 European Patent Office – Rijswik, Netherlands

The European Patent Office (EPO) Tower was completed in 1972 and is the only naturally ventilated building with over 24 floors in the Netherlands. The tower is the oldest building in a growing set of EPO buildings in Rijswik, which itself is a small town outside of *Der Hauge*. The main headquarters of the EPO is in Munich, Germany. The architect was R.D. Bleeker of Buro Buro Bleeker, with engineering by Ingenieursbureau Jongen NV. Technical information, as well as a building tour, were provided by the building manager.

2,300 people work at the Rijswik location, with 1,100 in the tower, and 1,200 in a newer, air-conditioned building. The number of complaints in the newer building is reported to be three times higher than in the tower. Sick-building syndrome, partially a result of 25% air re-circulation, has been attributed to increased illness in the newer building. Although the tower is near the 30 year old mark, the only major renovation to it was a two million dollar reinforcement of concrete that had been degraded by salty sea spray.

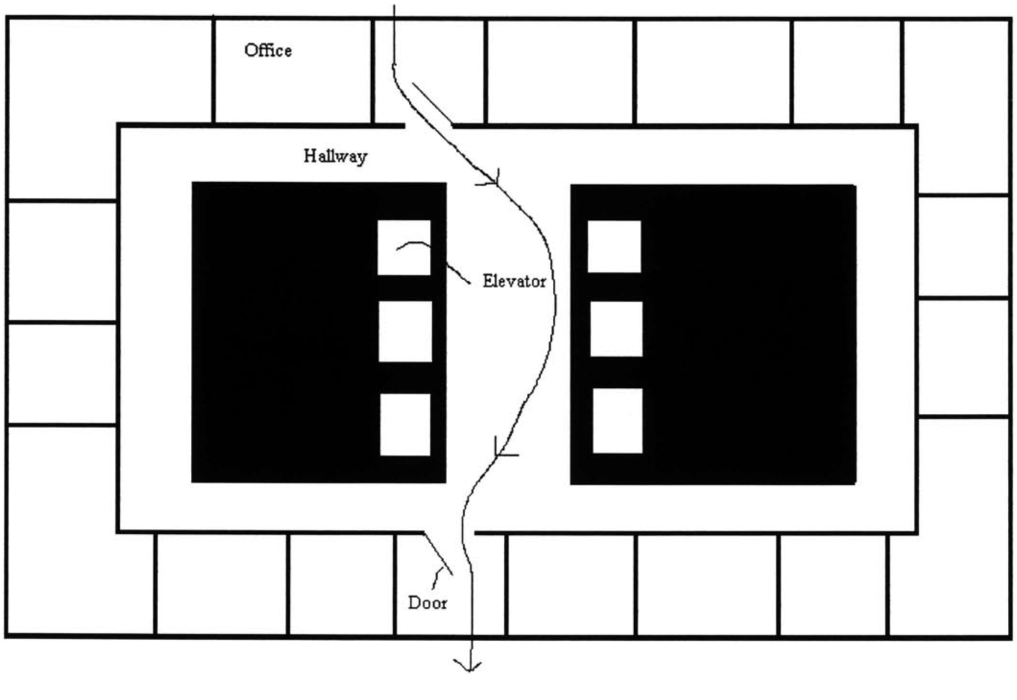


Figure 44 Schematic of typical floor. The line approximates the typical ventilation airflow path. In the schematic, doors in all offices, except two, are opened.

The building consists of a 25-floor, 86 m tall, rectangular tower. The diagonals of the building are NS and EW facing. The building features a high thermal mass construction, consisting of brick and concrete.

The building management system of the building is low-tech. There is no mechanism for automatic control of the blinds or windows in the tower. Yet, natural ventilation works reasonably well according to the building manager and several interviewed building occupants. Cross ventilation can be used effectively, given the fairly low-depth of the building. Offices all have windows to the outside, while the interior space houses conference rooms, copy rooms, elevator shafts, and stairwells. Cross ventilation will sometimes force papers to fly off tables, but workers have acclimated themselves to this inconvenience. Due to the significant amount of exposed thermal mass in the tower, studies show that large changes of outside temperatures result in very small changes in interior temperature. The climate in Rijswik ranges from –10°C to 30°C. A typical summer day is 22-23°C. It was pointed out that the Dutch and German workers prefer a temperature of 19ºC, while the Italian and Spanish prefer a temperature around 21-22ºC. Cultural differences within a single building can play an important role in any design decisions made.

Each office features four manually operated windows. These windows are located in vertical pairs on opposing sides of a fixed window in the middle. Operable windows tilt horizontally inwards into the room. The upper window measures 0.35 x 0.70 m in size, while the lower window measures 1.20 x 0.70 m in size. A set of "trickle" vents is located in the frame above the fixed middle window. The operable area of the vents is 0.06 m^2.

The tower building uses half the energy of the newer building, when compared by useable floor space. Heating is by natural gas, which costs approximately 1/10 that of electricity in the Netherlands. 48-inch long fluorescent tubes provide artificial lighting. There are usually two to three 50 W tubes in each room. The ceiling in the office rooms is made up of glued tiles, while the corridor ceiling is suspended. The floor to ceiling height in the offices is 270 cm. The door height is typically 220 cm. Blinds are vertical, translucent, and made of plastic or cloth (approx. 3" width), rather than the aluminum blinds which are found in more modern buildings. An external shading device consisting of a concrete band 0.6 m wide with three slits set 0.9 m from the façade serves as a solar radiation shield.

A significant amount of plant life can be found on the ground floor and in the first and second floor atrium. The atrium serves as a mixing bowl to the library and several large conference rooms. The parking lot located next to the tower is being placed underground to make room for a new park. The goal is to improve the air quality around the building, which is located in a steadily growing region of The Hague.

The primary energy usage is electricity. The complex uses approximately 24 million kWh per year for electricity. Heating consumes 1.3 million m^3 of natural gas per year.

Figure 45 Exterior view of tower building.

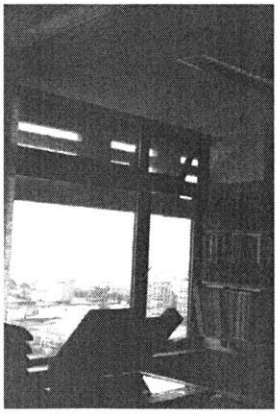


Figure 46 Typical office window unit. Note the integrated concrete shading device and the open window.

1.4.9 Inland Revenue Castle Meadows – Nottingham, England

Castle Meadows was designed to allow for as great as possible use of natural ventilation and daylighting. The design was done by Michael Hopkins and Partners with engineering by Arup. A tour, as well as technical data, was given by a facilities worker.

Castle Meadows consists of six four-floor office buildings and one multi-purpose arena. As a whole, over 1,800 people have worked at this site since its opening in 1994. There is no air-conditioning system at Castle Meadows. Solar heat gain is reduced using triple glazed windows, electronically controlled blinds, and external light shelves. The building management system automatically sets levels of heating, lighting, and ventilation. Artificial lighting, which principally consists of compact fluorescents, is controlled using fairly costly remote controls (approx. $110 US each). There are no traditional light switches.

Air enters the office spaces through doors and windows and is supplemented by under-floor fans that direct air through floor grilles. Fans can be controlled manually in each room at four different speeds. During the summer, warm air is drawn naturally from the lower three floors into glass stair towers. By natural buoyancy, hot air rises out of the towers. The roof of each tower is controlled by the building management system.

Radiators located below the floor grills in each room provide heating. The BMS is set to operate the radiators, but they can also be adjusted by means of a thermostat in each room. Windows are not automatic and are not controlled by the BMS. They can be tilted inwards (bottom pivot) or slid like a patio door.

A significant amount of exposed thermal mass can be seen in the building. The majority of the mass is located in the ceilings, which are made of concrete cast in the shape of waves. Approximately one-inch gaps between slabs of the concrete ceiling serve to increase the contact surface area to the air. Most doors, which are normally closed, are made out of glass. The floor is carpeted, an impediment to night cooling. Between four to six people share an office. Each office receives daylight with the aid of external light shields that direct light towards the ceiling. Interior offices are adjacent to large courtyards and also receive abundant amounts of daylight.

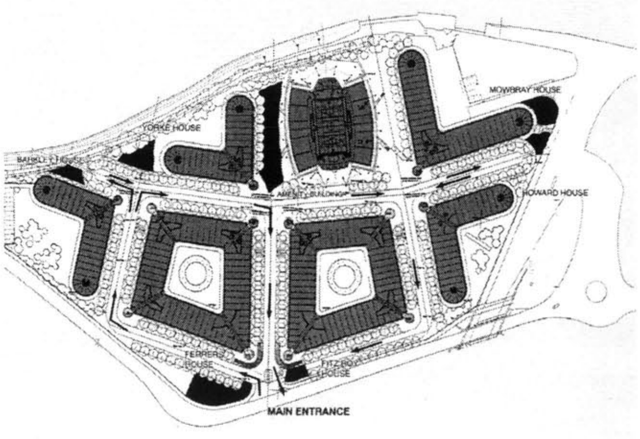


Figure 47 Site map. The arrows indicate fire escape routes. The complex at top middle is a sports arena.

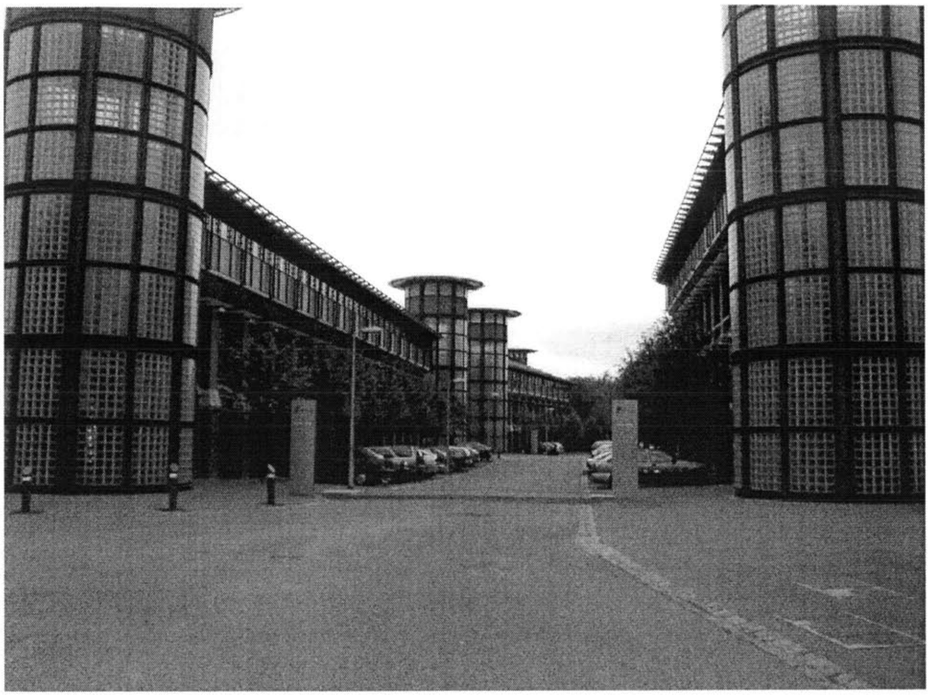


Figure 48 Exterior view. The building site consists of two diamond shaped buildings, 4 L-shaped buildings, and one sports center.

Brief interviews with occupants revealed some discontent with the building. The upper level, which features operable skylights and a fairly light construction sloped roof, reaches uncomfortable temperatures during the summer. The top floor is isolated from the lower floors through the use of highly insulated and airtight doors. The reason for this is to maintain proper airflow through the lower floors to the stairwell stacks. The main complaint over the lower floors regards the existence of drafts when stack effect ventilation is being used.

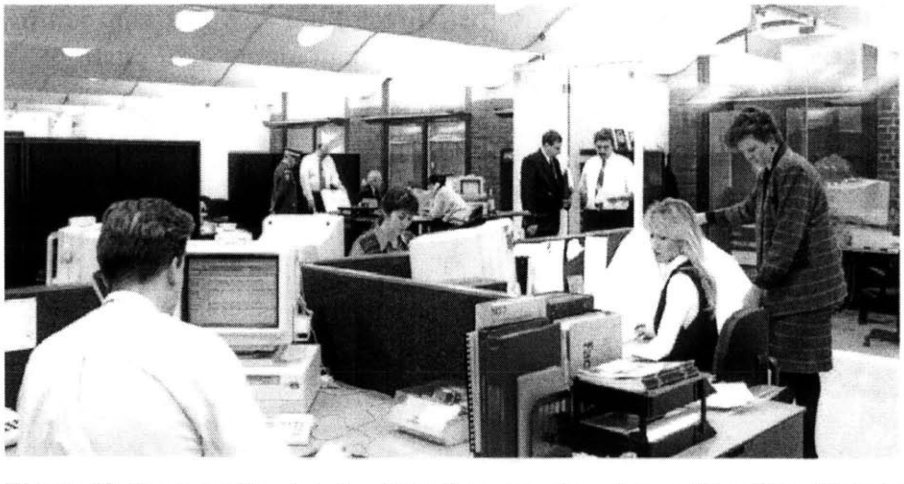


Figure 49 Typical office interior. Note the wave-shaped concrete ceiling. *Picture Courtesy of Inland Revenue Facilities Management Unit.*

Figure 50 "Mushroom" tower. These towers are used to provide stack ventilation to the lower three floors. The roof of the tower is opened automatically when indoor temperatures have gone past a certain setpoint.

Figure 51 Representative façade. The horizontal bars on the lower three floors are safety railings. Windows open horizontally into the room or can be moved to the side like a typical sliding glass door. Note the external light shields on the third floor. The top floor, featuring a relatively low mass ceiling is reported to be uncomfortably warm during some periods of the summer.

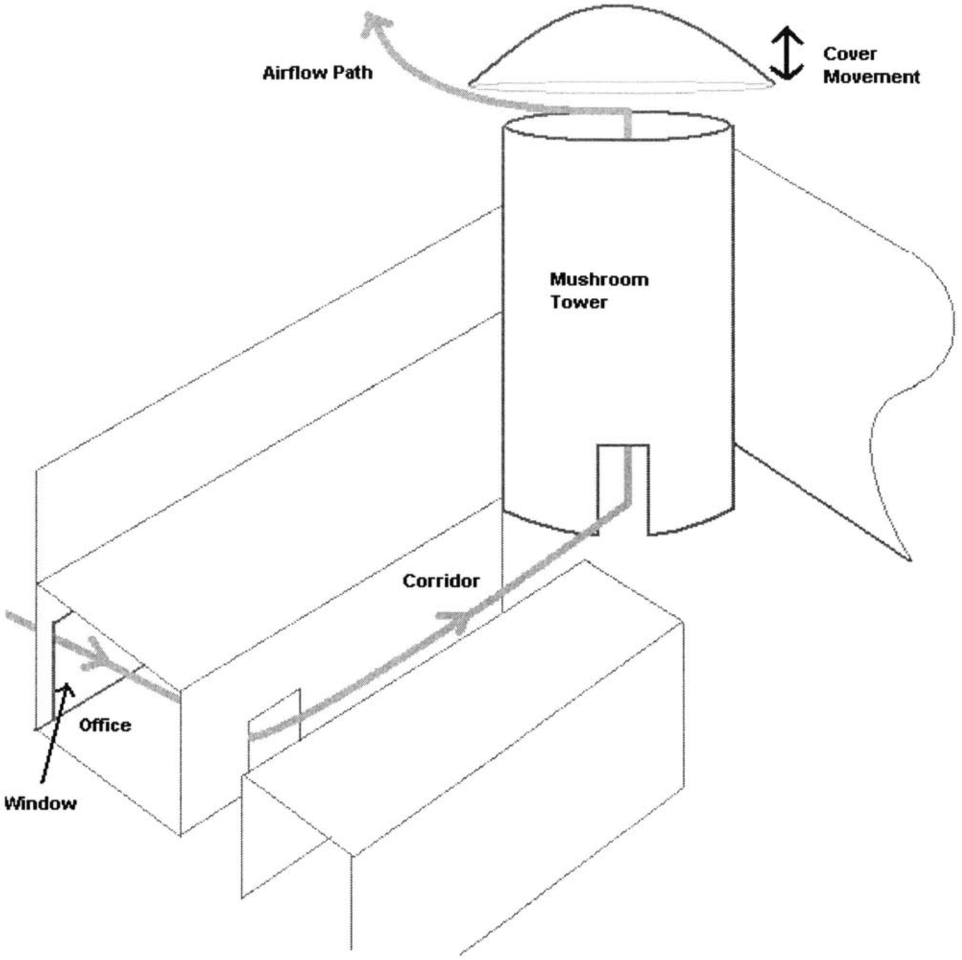


Figure 52 Diagram of airflow path through building.

1.4.10 University of Nottingham Jubilee Campus – Nottingham, England

In August of 2000, when this building site was visited, little was known about the performance of the building. Since then, the site has matured; it is reported to function well. The campus, which features all naturally ventilated buildings, opened in November of 1999. The design of Jubilee Campus is the work of Sir Michael Hopkins and Partners, whose previous projects include the Inland Revenue Center, in Nottingham, and the new Parliament Building at Westminster. The campus was completed at a cost of approximately 80 million US dollars with services engineering by Arup.

The main building, which houses classrooms, lecture halls, and offices, features operable windows both to the outside and to atriums spaced evenly within the complex. With the primary exception of lecture halls, all occupied spaces receive abundant amounts of daylight.

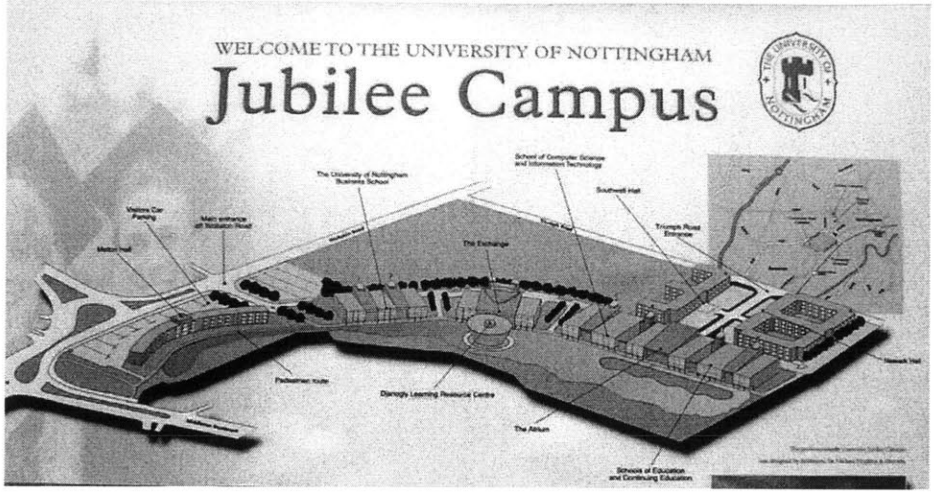


Figure 53 Site map. The left portion, as well as the top right portion of campus, features dormitory housing. The building in front of the circular library building is the student union.

In theory, the main building is cooled using a lake-effect breeze. An artificial pond spanning one entire side of the main building was designed to enhance this breeze, which is ejected through vents in the ground level floors. The designed airflow path is through interior corridors into offices and classrooms and then out through windows either to atriums or the outside. Atriums feature automated awnings that can open to provide a significant amount of exposure to the outside. A stairwell located at the end of each atrium (opposite the pond) is used for stack-effect ventilation. At the top of each stairwell is a wind sail that follows the optimal wind direction with the aid of a photovoltaic powered motor.

Nighttime cooling is used. All lighting, windows, and shades can be automatically controlled by the BMS. Offices and classrooms feature concrete ceilings and fluorescent lighting.

In August 2000, interviews with occupants indicated that the system still had some glitches that needed to be resolved. The pond was partially drained at the time of our visit due to leakage. Windows were not able to operate automatically. The overall sentiment was that the system didn't work well, but would work in the future, which is indeed the case in 2002.

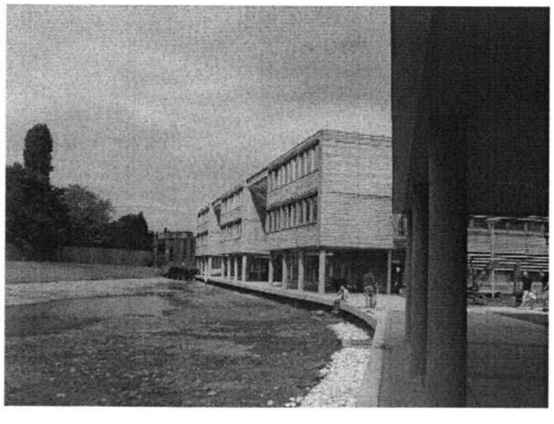


Figure 54 Main building. The lake in front of the building was drained due to leakage problems.

Figure 55 Operable shutters of one of the main building atriums.

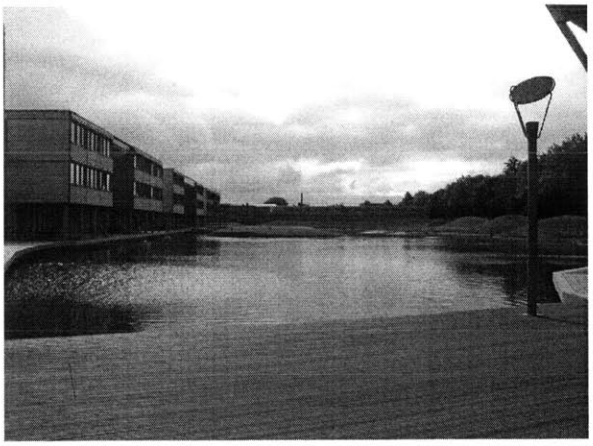


Figure 56 Man-made lake. A south to north breeze across the lake provides cooling to the main campus building.

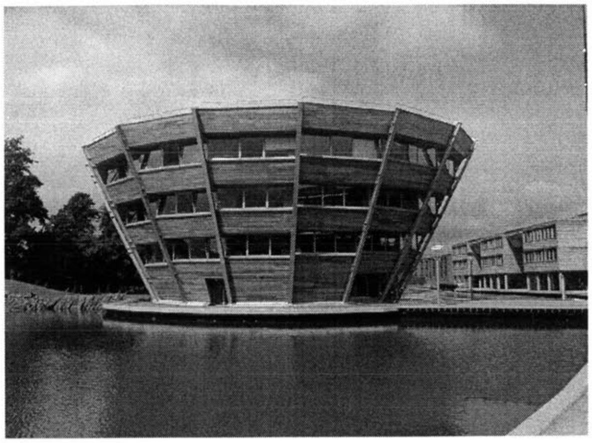


Figure 57 Learning Resource Center (Library). This building is wholly naturally ventilated and is a dominant feature of the campus.

Figure 58 Backside of main campus building. The vertical wind sails can rotate to provide optimal exhaust of air from the front of the building. The small windows on the left open into restrooms and kitchen facilities.

1.4.11 Queens Building – Leicester, England

The Queens Building opened in 1993 and houses 1,500 full-time students of the School of Engineering and Manufacture of De Montfort University. Short Ford Associates, a firm that had previously designed natural ventilated buildings for the warm climate of the Mediterranean, designed the building. They realized that the Queens building had to have a highly insulated, thermally massive envelope with a low depth plan and generous ceiling heights that would promote natural ventilation and daylighting. From the university administration's perspective, they wanted a building that would serve as the centerpiece of a massive effort to rejuvenate a dilapidated campus. Constructing an innovative, environmentally friendly, and user-friendly building was essential. A tour of the building, as well as technical information, was given by the building manager. Data was also provided in a BRECSU publication (1997).

After four years of design and construction, the Queens Building was opened to great acclaim. The Heating, Ventilation, and Cooling Association selected it as Green Building of the Year in 1995. It is most remarkable that the building, with over 10,000 m^2 of floor space, is wholly naturally ventilated.

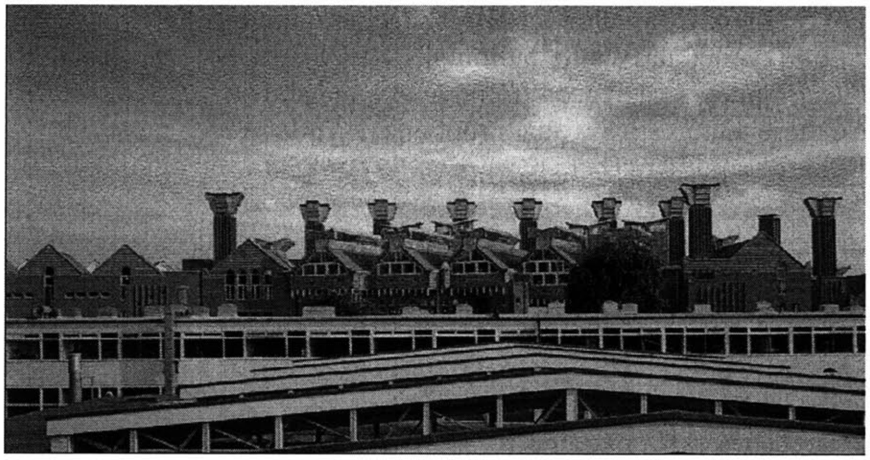


Figure 59 Exterior view. Note the stack outlets on the roof, as well as the predominantly brick structure.

Three classrooms on the ground level feature ventilation using stack ventilation. There are two 13.3 m tall stacks for each classroom, which provide a 4.0 m^3/s volume flow rate. Motorized dampers in each stack are adjusted by the BMS. Manually operated windows on the opposing side (south side) of the stack vents provide cross ventilation. Each classroom is designed for 54 students. The system was designed for a peak outdoor temperature of 28 to 29°C, although occasionally there are summer peaks of up to 33°C. During the winter, outdoor temperatures reach as low as – 4°C. Building engineers feel the classrooms are over-ventilated.

There are a variety of room layouts in the Queens Building. The largest space houses machine tools for the mechanical engineering department. The room features a two-story open plan with automated roof vents. The vents take approximately 25-30 minutes to open, but shut quickly during rain. Sodium discharge lamps provide the 1,000 lux needed for the operation of machine tools. Ventilation is provided using perforated brick stacks, as well as the roof vents mentioned before. A volumetric flow rate of 3.6 m^3/s can be achieved.

There are two 160-person lecture halls featuring a fairly steep seating profile. Vents located underneath each level of seating provide displacement ventilation to two high volume stacks (one can be fan-assisted to start stack effect) located behind the lecturer podium. The stacks are operated with input from carbon dioxide sensors when a lecture hall is in use. To avoid drafts, fresh outdoor air is heated to a minimum temperature and dampers in the stack close if the temperature in them is less than 12ºC. Sensors prevent the dampers from opening more than halfway if there is a risk of rain entry. Some other notable elements in each lecture hall include a perforated wood wall with acoustic insulation and school-made fluorescent lighting fixtures. The lecture hall was fairly cool and comfortable during our visit.

The top floor, which is not physically separated from the tall atrium of the building, features a large computer cluster. The ceiling features a repetitive V-shape profile with operable ridge vents. The vents were not in operation, until the summer of 2000, because their actuating mechanisms broke shortly after the building opened in 1993. Contractor disputes prevented their repair for seven years.

Energy consumption for the first year of operation was 114 kWh/m^2 for gas and 43 KWh/m^2 for electricity with a CO_2 emission of 53 kg/m^2. Based on the British Department of Energy's guidebook, this is about half that of a typical university building [BRECSU, 2000]. According to the building manager, the notable complaints have been from faculty and staff located in offices on the top floor. The office space there features a low mass roof and is said to reach very uncomfortable temperatures during the summer. There have been no complaints about other portions of the building.

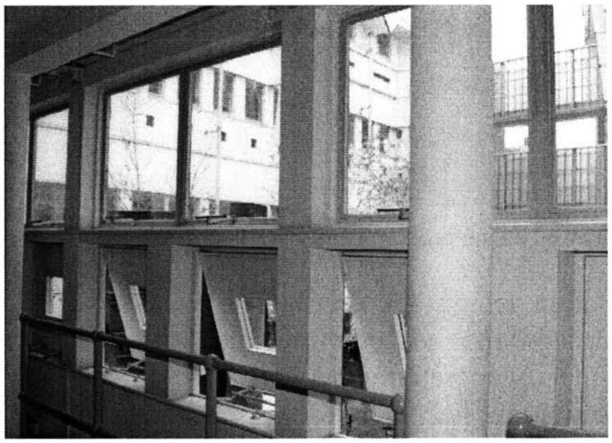


Figure 60 View of typical façade in electrical engineering laboratories. Windows are manually operated.

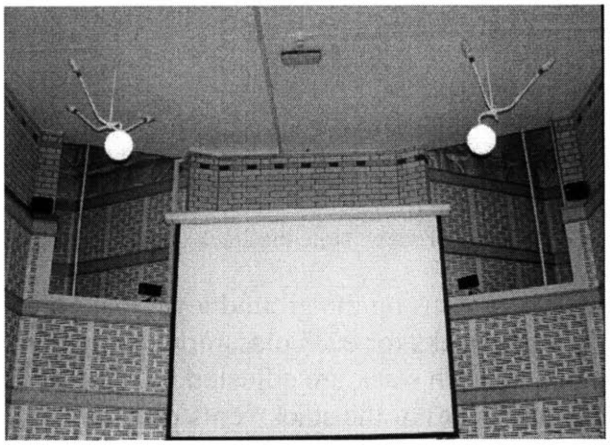


Figure 61 Openings to vent stacks (located to the left and right of the projector screen) in one of the two lecture halls. De Montfort University engineering students built the light fixtures. They consist of three compact fluorescents and one globe light.

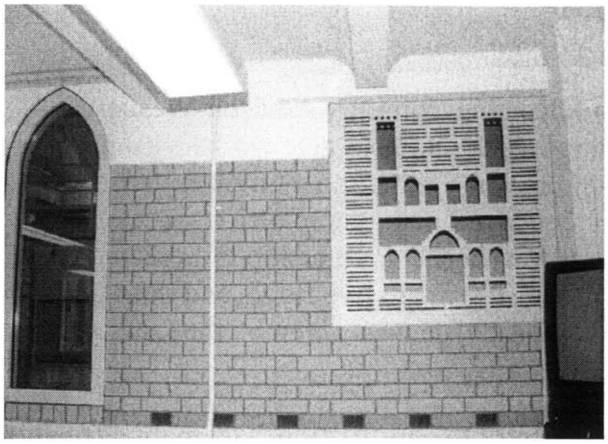


Figure 62 On the right is a highly ornamented grill to one of two ventilation stacks in this particular classroom. The window on the left continues the architectural motif followed throughout the building. The other vent is located on the same wall approximately 20 feet to the left of this vent. During the winter, heavy drafts can occur when cold air begins to drop down one shaft, while hot air rises up the other shaft, creating a U-shaped flow pattern.

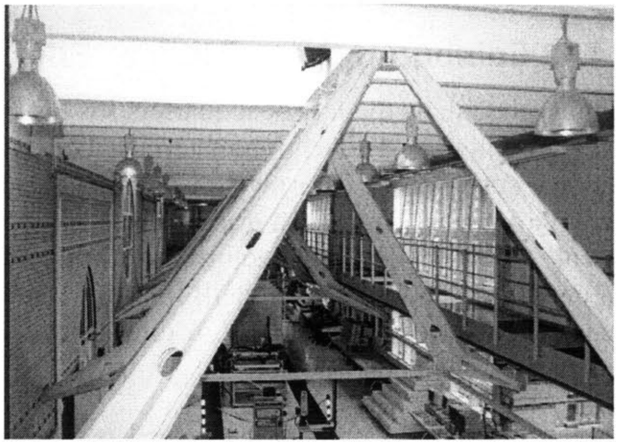


Figure 63 Mechatronics lab. In part, by having a two-story space, even with high heat-loads due to large equipment, air-conditioning is not required. The V-shaped supports allow for the maximum possible use of floor space.

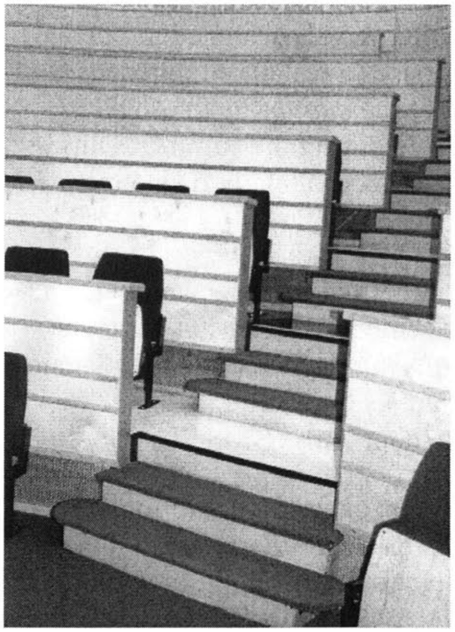


Figure 64 Lecture hall seating. Note the vents located behind each row of seats. The space behind this seating area is hollow and opened to the outside for natural ventilation.

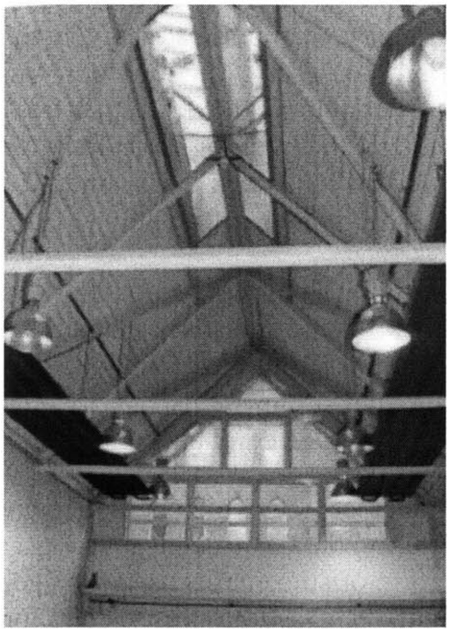


Figure 65 Mechanical engineering lab. At the top of this picture are motor-operated ridge vents. The inverted V-shape of the ceiling collects hot air and channels it out through the vents. A similar ceiling arrangement is featured on the top floor of the building. The actuators to the vents on the top floor were not made robustly enough and failed within a few weeks of the opening of the building, eliminating a critical component of the ventilation system. Skylights and gable glazing are used often to provide high levels of daylighting. In areas where artificial lighting is used, occupancy sensors are used to reduce energy consumption.

1.4.12 Edinburgh Gate – Harlow, England

Edinburgh Gate is the UK headquarters for Pearson Education (formally Addison-Wesley), a leading publisher of education materials. The building was designed to give workers as much personal control over their own environment as possible, while at the same time being friendly to the environment. This was a priority over other goals, such as having more office space or upscale furniture. The architecture firm for the project was the CD Partnership in London. The engineering was done by Cundall, Johnston, and Partners. There are five floors and three atria for a usable floor area of 16,000 m^2. A tour, as well as technical data, was given by the facility manager.

The building, completed in 1995, faced several hurdles prior to construction. The main difficulty early on was getting zoning permission to construct it. Zoning officials initially did not understand why Pearson wanted to build a new building, when space could be rented out in existing buildings at a lower cost. Eventually, Pearson was able to convince officials that its needs would not be met unless it had a building constructed from scratch.

Since its opening, the building has performed well, based on studies done by the Building Research Establishment (BRE). In 1995, it was voted the most environmentally sound building in the UK by the BRE.

Natural ventilation is the primary ventilation strategy, but the building was designed to operate using a mixed-mode system if necessary. The top floor, which houses a restaurant, kitchens, and conference rooms, is fully air conditioned, while other floors have the *capability* to use air-conditioning. In essence though, the building is naturally ventilated during the summer. During the winter, fresh air is supplied mechanically and windows are only occasionally opened to provide fresh air. The overall set point for Edinburgh Gate is 23°C.

Night cooling is possible with the significant amount of exposed thermal mass located in floors, support columns, and ceilings. The ceilings, in particular, are 300 mm thick slabs of concrete. With outside temperatures ranging from the high 20's to low 30's, interior temperatures remain steady at 26 to 27°C. When night cooling is used, slab temperatures are lowered to 20°C. Temperature sensors embedded in the concrete ceilings provide input to the BMS.

Electricity is used at night to create ice, which is used to chill water for the air conditioning. Ice is built at night instead of during the day to take advantage of lower electricity rates. In the atria, under floor heating in the form of silica gel is used. The gel is liquefied overnight; the liquid then slowly releases heat during the day, as it returns to solid form.

Control of heating is managed by the BMS, which operates on 5-day data. Heating is not used during the summer, while natural ventilation is only used when an indoor temperature of over 20°C has been reached.

Offices are located on the first through fourth floors. An under-floor void acts as a plenum for fresh airflow during the winter. Cabling is also routed through the plenum. T8 fluorescent fixtures provide indirect lighting at an intensity of 350 lux. Each light fixture has two plugs, one to interface with the BMS and one for power. Lights are automatically turned off at the end of the working day, while each office receives daylight through both the exterior façade and from one of three large interior atriums.

The atriums feature automated operable windows at the top level for stack ventilation. Two roof-mounted weather stations provide input to the BMS. Office windows adjacent to the atrium are operated manually, as are windows on the exterior façade. Interior roll-up blinds are also manually controlled. Venting louvers, which are always open, are located along the top of all atrium-facing windows. Generally, the building staff does not close windows at the end of the day. Window and blind settings are set by individual users and not interfered with.

As an aid to cross ventilation, office doors are sprung in a fully open position. An occupant must physically close and latch a door to keep it closed. In addition to this, office cellularization is kept to a minimum of 25-30% of floor space.

Figure 66 Exterior view. The large parking lot in front of the building is deliberately shown as a possible pollution source.

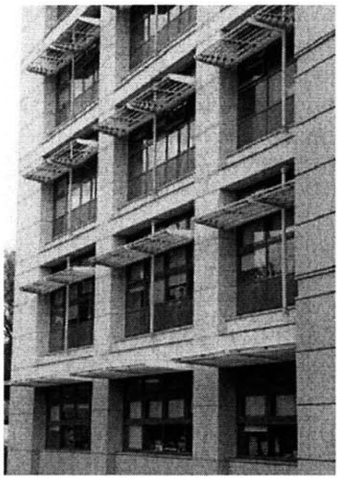


Figure 67 Outer façade. The protrusions between the top and middle operable windows act both as shades and reflective pans, directing sunlight through the uppermost window of each façade element onto the ceilings in office areas.

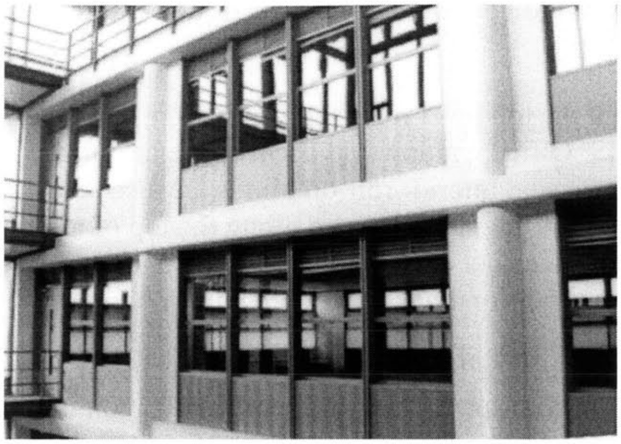


Figure 68 Partial view of interior atrium façade. There are three atriums, which allow the building to be rented out to three different tenants if necessary. Some tenants may choose to run the building with just natural ventilation, while others may choose to use air-conditioning. The building, considered to be mixed-mode, is flexible to suit occupant needs.

Figure 69 General view of office space. Both the ceiling and the posts are concrete and help with effective night cooling.

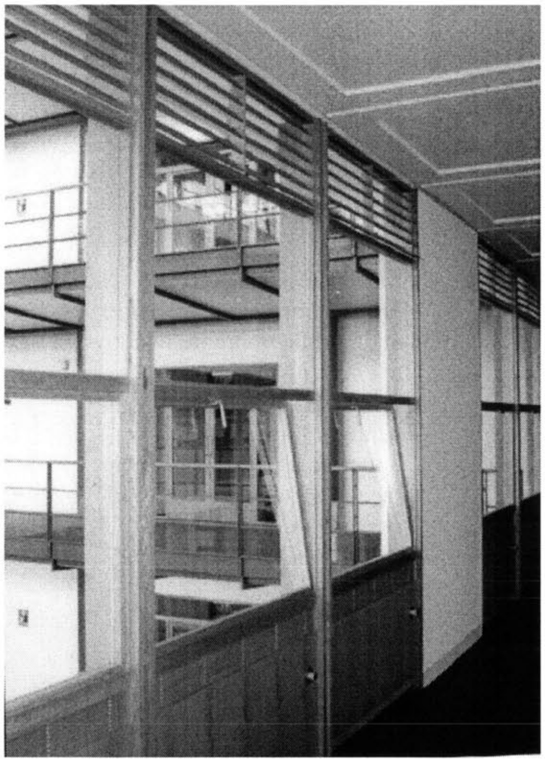


Figure 70 Office façade to atrium. The lower windows can be opened manually for ventilation to the atrium. The top louvers are fixed in an open position. The grills below the window provide heating air. The knob at the bottom right of each grill is for heat control.

Figure 71 Office façade to outside. Note the lowered shading device on the left window. The top tilt window is frosted to smooth out sunlight and thus reduce glare. Both the top and middle windows are manually operated.

Figure 72 Top-level atrium façade. The windows at the top of the façade are actuated by pistons and opened when stack ventilation is necessary.

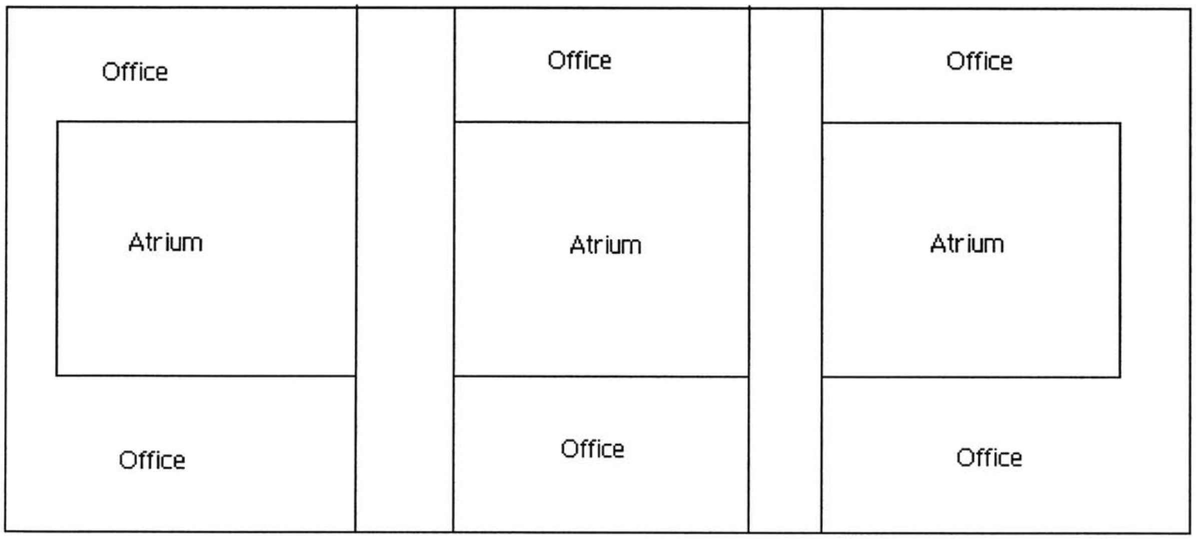


Figure 73 Approximate schematic of the building's floor plan. Each of the three atriums is surrounded on the North and South by open plan offices.

1.4.13 BRE *Environmental Building* – Garston, England

The Building Research Establishment, located in Garston, England, is a set of research laboratories that creates standards for building construction and operation through technical analysis done with modeling and experimentation. In an effort to set a good example to the rest of the UK, BRE opened a new building called the "Environmental Building" in 1999. The architecture firm was Feilden Clegg Architects with engineering by Max Fordham and Partners. There are three floors with a usable area of 2,000 m^2. The entire building is in itself a large-scale experimental facility for sustainable design. A tour was given by one of the researchers in the building.

According to a member of the staff, the target energy consumption was 47 kWh/m^2 for gas and 36 kWh/m^2 for electricity. The actual energy consumption has been about 120 kWh/m^2 combined. The reason for the discrepancy has been attributed to occupants opening their windows more during the winter for fresh air than expected. According to research done at BRE, occupants have experienced approximately 20% better productivity during the summer compared with standard office buildings. There was no change in productivity during the winter.

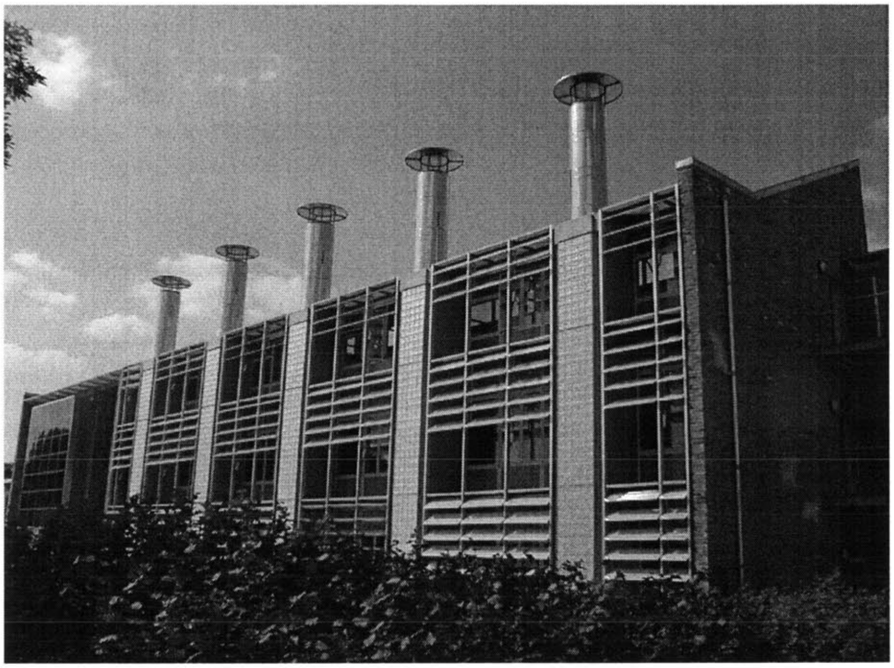


Figure 74 South façade view.

The Environmental Building focuses on several key factors in sustainable building design, such as daylighting, natural ventilation, night and groundwater cooling, lighting, recycling, and intelligent controls. Movable external louvers are installed on the south side of the building to reduce solar heat gain, allowing regular blinds to remain up during the day for maximum day lighting. Both cross ventilation and stack ventilation are used in the building. Cross ventilation is used effectively on windy days given the narrow-depth of the building (13.5 m). There is a 7.5 meter wide open plan area, while a 4.5 meter wide area is dedicated to cellular offices. Stack ventilation is used on days when there is little or no wind to ventilate the first and second floors.

During the summer, air enters either through open windows or through exterior openings into wavy and hollow concrete ceilings. The ceiling slabs are used to absorb heat during the day and are cooled down during the night. Naturally cooled groundwater is run through pipes embedded in the floor to provide additional cooling.

The building management system controls the lighting. The system automatically compensates for daylight levels and occupancy, controlling each light individually to provide 350 lux. The operation of windows, external louvers, and heaters is also automated. Occupants can override presets at any time. A 47 m^2 photovoltaic array located on the south side generates between 3 to 4 kW.

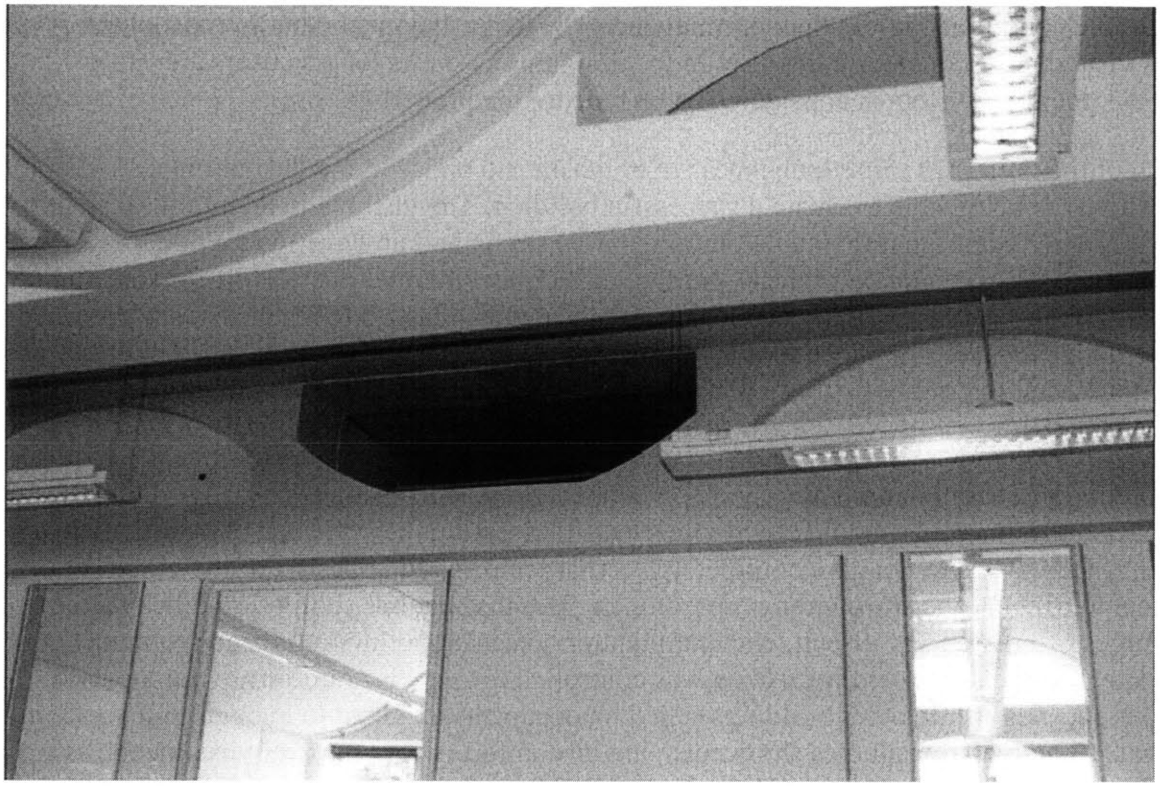


Figure 75 Ceiling view. The hollow void allows fresh air to enter directly from the outside.

1.4.14 Europe Trip Summary and Conclusion

The Europe Trip provided insight into the variety of ways natural ventilation can be implemented. Because the summer of 2000 was relatively mild compared to previous summers, we were never able to experience first-hand how well each building performed on a subjective level. We do know that the buildings are generally well liked by their users. Technical data shows that a significant amount of energy is saved using passive design.

Form, the building envelope, and spatial layout are critical to determining a building's energy performance. Suitable climate conditions can be attained in buildings with high heat loads through a combination of exposure to thermal mass and carefully controlled natural ventilation. Most of the buildings discussed feature a significant amount of exposed thermal mass.

In designing an innovative, naturally ventilated building, the full support and involvement of clients, planning regulators, fire code marshals, and end users must be attained. For example, architects, such as Christoph Ingenhoven, the lead planner for the RWE tower, were willing to take the extra effort to work with fire code regulators to create a more open plan for better airflow, as well as with specialists in façade engineering, to create a truly innovative and effective design.

Designers of the Edinburgh Gate building held sessions with end users to determine what they wanted in a building. The result is a well-liked building featuring a high level of individual user control. This user control appears not to get in the way of the overall performance of the building, even though the concern exists that giving users too much freedom can lead to uncomfortable conditions or less than optimal energy savings. It appears that in most of the buildings visited, user concerns came first in the design process. As long as users are comfortable, then the system is considered to be functioning properly.

With each of the buildings visited, openness to criticism and praise in the design process went a long way towards being able to create a successful building. The vision and attention to client needs of those behind these remarkable buildings, was strong and unwavering. While the buildings we visited may not be perfect— individuals do feel thermal discomfort for some parts of the year—on the whole, building occupants understand the reasons for their discomfort based on design choices made. The success of a building may not be judged by architectural journals or building engineers, but rather by those that will spend most of their time in the buildings—the workers.

The continuing increase in computing power available has made analysis of various building designs easier. Design tools should always be used for assessing the *potential* of a particular idea, even if they prove to not give completely accurate information. Design of the building form must take into account the surrounding environment. Because natural ventilation relies on the driving forces of nature to be effective, the amount of noise and pollution located around a building site must be accounted for. Noise was controlled for sky-rise buildings with the use of double-skin facades, while other buildings relied on occupants to adjust to background noise. In fact, it should be noted that studies show occupant discomfort in low-noise environments, as much as high-noise environments [ASHRAE, 1997]. When done properly, exterior noise can be harnessed to bring a greater connection of occupants to the environment.

There are some misconceptions associated with passive design. One is that it limits the opportunity to create stimulating environments and limits architectural freedom. While not every building will be able to satisfy everybody, most of the buildings visited have been recognized as being architecturally innovative in their own right.

The cost of an innovative naturally ventilated building does not need to be any higher than that of a conventional one. In cases where initial capital costs are higher than for a conventional building, the cost savings due to reduced energy consumption and minimized or eliminated HVAC equipment can pay off the difference in a matter of years. For example, the Victoria Insurance Tower, while costing several million dollars more to build than a conventional tower of similar size, has recuperated its additional investment in four years.

Designing a naturally ventilated building is on a whole more complicated than designing one with air-conditioning. The decision to use natural ventilation must be done at the very beginning of the design development process. Extra time must be given to ensure that the design is robust. Motors and other actuating mechanisms for windows, blinds, and other components, must be sufficiently reliable to handle repeated usage and high loads. Two notable examples of critical component failures are the mechanisms operating large pivoting windows in the Commerzbank winter gardens, as well as the actuators for the ridge vents in the De Montford University Queens Building. With systems like these out of commission, a dramatic reduction in performance can occur.

Once a building is completed, it cannot be left to operate solely on its own. Building management systems must be responsive and fine-tuned to provide optimal performance. The controls available to individual users should be easy to operate and understand within the framework of the building's overall operational strategy.

Perhaps the greatest lesson learned is that post-occupancy monitoring is essential to improving the performance of naturally ventilated buildings and to also convincing others to adopt natural ventilation as a major design strategy.

1.5 State of Natural Ventilation in the United States

1.5.1 Building Search

A review of the literature indicates that some natural ventilation thermal comfort studies have been performed in the western United States [de Dear, 1998] in recent years. Yet, in the eastern United States in 2000, there were very few recently constructed naturally ventilated or even mixed-mode buildings to begin with. Interviews with building engineers, architects, university professors, government agencies, and even ordinary office workers in the street, revealed a paucity of naturally ventilated buildings to potentially study.

1.5.2 Regulations and Guidelines

Natural ventilation in the United States is limited in part by rigid thermal comfort [ASHRAE, 1992] and indoor air quality standards [ASHRAE, 2001b]. Because of a push by several research organizations in the United States, these standards are in the process of being changed to include a provision for natural ventilation [Brager & de Dear, 2000]. Even with changes though, there has to be a way to motivate architects and engineers to specify natural ventilation in their designs. In various states and cities [NYSERDA, 2002; Santa Monica, 1994], some green building guidelines have been established. On a national level, the United States Green Building Council has established the Leadership in Environmental and Energy Design (LEED) Green Building rating system. The LEED rating system is a voluntary, consensus-based, market-driven system based on existing proven technology. The goal is to provide a way to determine the whole building performance over a building's entire life cycle. The general categories that a building can receive credit are: sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, and innovation and design process. Under the section regarding indoor environmental quality, there is a potential credit for natural ventilation. Credit 2.0 [USGBC, 2001] is worded:

> "For mechanically ventilated buildings, design ventilation systems that result in an air change effectiveness (E) greater than or equal to 0.9 as determined by ASHRAE 129-1997. For naturally ventilated spaces demonstrate a distribution and laminar flow pattern that involves not less than 90% of the room or zone area in the direction of air flow for at least 95% of hours of occupancy."

The 95% and 90% requirement appear to be fairly stringent. The guidelines leave much to be desired in how the requirements would be validated in a real building. Another way to achieve credit is to use natural ventilation as a method to reduce energy consumption under Credits 1.1-1.5 under the energy and atmosphere section:

> "Reduce design energy cost compared to the energy cost budget for regulated energy components described by the requirements of ASHRAE/IESNA Standard 90.1-1999, as demonstrated by a whole building simulation using the Energy Cost Budget Method described in Section 11. New Buildings: 20% (2 pts), 30% (4 pts), 40% (6 pts), 50% (8 pts), 60% (10 pts)."

The LEED rating system is still in the process of being revised based on feedback from a variety of sources. As of now, there are not many LEED rated buildings. It is possible that builders are following some of the guidelines, but not actually applying for certification. Even with the LEED rating system though, there really was little incentive to use innovative systems, until recently.

Those that pay energy costs have not been the same people that commission a new building in the first place. Now though, some utility companies will give significant rebates to builders that incorporate features that reduce overall energy consumption.

1.5.3 European Research and Organizations

In Europe, much work has been done on natural ventilation. Among the work is two fairly large, multi-nation research projects: PASCOOL and NatVent. PASCOOL is a European research project with emphasis on the use of passive cooling techniques and systems in buildings. The work was undertaken to cover existing scientific gaps and to increase general knowledge on passive cooling topics. The project combined an interrelated set of research actions under various topics with the following objectives [Santamouris et al., 1996]:

- To create weather data sets for cooling applications.
- To define thermal comfort criteria for indoor spaces.
- To evaluate the micro climatic enhancement and the applicability of natural cooling techniques in Europe.
- To develop solar control techniques for all year performance, encompassing thermal and daylighting aspects.
- To investigate the role of the thermal inertia in free-running and air-conditioned buildings.
- To investigate the airflow patterns inside and around buildings and of the role of ventilation as a cooling resource.
- To integrate the outcomes of the above research topics into a diagnostic, pre-design assessment tool and the definition of design guidelines for various building types in Europe.

The research methodology of the overall project was based on an extensive experimental campaign based on test cell experiments, monitoring of selected buildings, and laboratory experiments. The participating countries included Belgium, France, Greece, Italy, Portugal, Spain, Switzerland, The Netherlands, Great Britain, Slovenia, Hungary, and Bulgaria. The project lasted 27 months and was completed in 1992.

The NatVent project was completed more recently. Seven counties: Great Britain, Belgium, Denmark, The Netherlands, Sweden, Norway and Switzerland participated in the project. The goal of the project was to reduce primary energy consumption and CO_2 emissions in buildings on two levels [Perera, 1998]. The first was to provide solutions to barriers that prevent the adoption of natural ventilation and low-energy cooling in countries with moderate and cold climates. The second was to encourage and accelerate the use of natural ventilation and smart control systems as the main design option in new and retrofitted commercial buildings.

The project was targeted at countries with low winter and moderate summer temperatures where summer overheating from solar and internal gain can be significantly reduced by using properly designed natural ventilation. Solutions for buildings in urban areas where external air pollution and noise are high were also treated as a priority.

19 buildings were evaluated for the NatVent projects [Perera, 1998]. Both thermal comfort surveys and field measurements were taken. Typically, very detailed monitoring took place at each of the buildings during one peak summer week. Tracer gas measurements of air change rates were taken, along with dry bulb temperature, mean radiant temperature, air velocity, and humidity measurements. A detailed analysis of unique design features of each building was also done. Reports of the monitoring for all 19 buildings are available [Perera, 1998]. A thermal model was made that predicts building performance for various climate and building orientations and layouts [Svensson & Aggerholm, 1998].

There are also research organizations that focus primarily on building issues. One example is the Building Research Establishment (BRE) in the United Kingdom. The BRE performs research on all aspects of building design, including natural ventilation [BRE, 2002a]. It created a very well known assessment protocol known as the Building Research Establishment Environmental Assessment Method (BREEAM). BREEAM is a voluntary program that allows building owners and occupants to find out about their impacts on a variety of environmental factors, including ozone depletion, global warming, and the destruction of rainforests and other resources [BRE, 2002b]. It also illuminates a number of other building issues, from noise and air pollution to lighting and hazardous materials. An interesting thing to note is that the BREEAM features more than 600 points, while the LEED system has 69. BREEAM measures energy reduction in units of carbon emissions, while LEED measures it in units of dollars.

In addition to the BRE, there are also organizations with members from around the world. Among the most known are the International Energy Agency (IEA) and the Chartered Institution of Building Services Engineers (CIBSE). In recognition of the significant impact of ventilation on energy use, combined with concerns over indoor air quality, the International Energy Agency (IEA) inaugurated the Air Infiltration and Ventilation Center (AIVC) in 1979. The role of the center is to provide technical support to those involved in the research and development of ventilation technology as well as to ensure the widest dissemination of information on related energy and air quality issues [AIVC, 2002]. The CIBSE undertakes a wide range of activities including: producing information services and acknowledged industry good practice publications, running a wide range of events, and providing extensive networking activities through a series of regional and special interest groups [CIBSE, 2002].

There are also annual conferences around the world that encourage paper submissions covering topics related to natural ventilation. One particular conference that has produced a large body of material is the RoomVent conference. SCANVAC, the Scandinavian Federation of Heating, Ventilating and Sanitary Engineering Associations in Denmark, Finland, Iceland, Norway, and Sweden initiated the RoomVent conferences in 1987. The aim of the conference is to bring together researchers from universities and research institutes, engineers and consultants from industry, government officials, and policy-makers involved with indoor environment design, to discuss the current state of the art, and to identify paths for future development. The latest techniques for visualization, measurement, analysis, and computer simulation of airflow generated by mechanical or natural means, in spaces occupied by people, are addressed [RoomVent, 2002].

1.5.4 United States Research and Organizations

Research on natural ventilation is sponsored by various organizations, including the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE), the National Institute of Standards and Technology (NIST), the Lawrence Berkeley Laboratory (LBL), the Department of Energy (DOE), and the National Renewable Energy Lab (NREL). ASHRAE's participation in natural ventilation research takes place on several fronts, such as annual conferences, sponsorship of projects by third-party organizations, and the publication and development of standards. NIST, LBL, NREL, and other government laboratories also take on a variety of laboratory and computer based research. Yet, very little post-occupancy monitoring of actual buildings is done, except in the western United States. One program that seeks to fill this void is the DOE's high performance buildings project. The goals include: developing high-performance design, construction, and operation processes, providing tools for crafting high-performance buildings, researching new technologies for high-performance buildings, defining the criteria and methods for measuring building performance, measuring and documenting building performance in high-profile examples, and transforming the marketplace [DOE, 2002].

NREL has also made some efforts to monitor some buildings for their energy performance, but otherwise, even in 2002, little has been done to look at buildings, in the eastern United States, specifically for their natural ventilation performance.

There are also regional and local organizations that promote natural ventilation design. One particular organization that has gained prominence is the Northeast Sustainable Energy Association. Their annual conference attracts many highly motivated engineers, architects, educators, and students [NESEA, 2002]. As discussed before, some cities have established green building guidelines. While most guidelines are not mandatory, they at least give organizations a framework to base their designs on.

Finally, architecture and building related programs at a select few universities in the United States are training future professionals with knowledge of sustainable design, including the concept of natural ventilation.

1.5.5 Research Motivation

As discussed earlier, there has been little post-occupancy monitoring of naturally ventilated buildings in the eastern United States. While research on other fronts has been progressing, monitoring continues to receive little emphasis. It is presumed that once a building is occupied, any problems uncovered by monitoring will cause more headaches and may result in legal liability for the architects and engineers involved in the project. Even if all responsibility is waived, there is a presumption that very little can be done if any problems are indeed found [Preiser, 1989].

An equally important consideration is cost. Typically, no money is budgeted for post-occupancy monitoring. Purchasing appropriate equipment can easily cost thousands of dollars. Additionally, a significant amount of man-hours is needed to gain a good picture of a building's operation.

Even with all the concerns associated with monitoring, much can be learned from the process, as was seen in the European NatVent project. With monitoring, we continue to learn about how occupants adapt to a naturally ventilated environment. We are also able to see how well various building energy simulations function and how well new technologies work. With studies in the eastern United States, monitoring could show that natural ventilation can work in buildings situated in a hot and humid climate, rather than just the arid climate of the western United States. A good understanding of a couple high-profile buildings could be enough to incite more architects and engineers consider natural ventilation in their designs.

1.5.6 Research Implementation

While several naturally ventilated buildings in California were located, very few buildings in other parts of the country were found. In fact, some of the organizations called laughed at the idea of natural ventilation. They wondered why anyone would choose natural ventilation over mechanical ventilation. On the other end, some organizations expressed great interest and support in this research, but lamented over the fact that our culture is very dependent on mechanical ventilation. Finally, some organizations expressed that they had tentative plans to monitor the performance of various green buildings, including some that use natural ventilation. Yet, as of April 2002, very few buildings are actually being monitored.

Originally, it was proposed that three buildings be selected for monitoring. After months of searching, only two suitable buildings were found. The criterion used in selecting buildings was:

- Natural ventilation specified as a dominant cooling strategy by the architect
- Use of cross and stack ventilation
- Greater than 5,000 square feet
- Non-residential or industrial
- Located in the northeastern United States (north of North Carolina and east of the Appalachian Mountains)
- Reasonable access to all parts of the building
- Excess of 90°F (32.2°C) days with up to 80% RH during non-rainy periods

One of the buildings is located in Natick, Massachusetts, a suburb 15 miles west of Boston. It is a nature center run by the Massachusetts Audubon Society, the largest environmental group in New England. The other building is located in Annapolis, Maryland. The Chesapeake Bay Foundation, another very large environmental group in the mid-Atlantic region, owns the building. It is not surprising that two environmental groups work in these buildings. Environmental groups have typically adopted green technologies before more traditional clients.

Chapter 2 Broadmoor Wildlife Sanctuary Description

2.1 Introduction

The Broadmoor Wildlife Sanctuary's nature center is located in South Natick, Massachusetts (42.29°N, 71.35°W). Originally a barn, the center was retrofitted in 1983. Its interior was modernized, while retaining much of its original exterior shell. The architect leading the design was Gerard Ives, well known in the Boston area for passive solar buildings. The Broodmoor Wildlife Sanctuary itself features nine miles of walking trails. The overall dimension of the building is 70' x 40' (21.3 x 12.2 m) over 4 floors, two of them occupied. The floor-to-ceiling height is ten feet. The building is in a medium density residential area.

The primary feature that sets the nature center apart from most buildings is its use of passive solar heating. A two-level closed sunspace on the south façade captures heat during the day. Air reaching 160°F is moved from the space by fan into occupied spaces on the main floor, as well as into bedrock beneath the building. The thermally massive basement floor serves as a radiant floor as heat is slowly released from the bedrock. This system allows the building to remain comfortable even during the coldest days without supplemental heat. During long stretches of cloudy days, a wood stove can be used.

Originally, the Massachusetts Audubon Society looked into the installation of a mechanical ventilation system, but due to a limited budget, natural ventilation was opted for. Passive cooling was specified in the design with numerous features, including an exterior wind shed designed to channel wind into the building (see Figure 100). During the summer, full-size doors are left completely open at all times to take advantage of night cooling. Each door has wooden louvers, as well as screens. The first is for night security and rain protection; the second is to keep out insects. These doors are located on two opposing sides of the building for cross ventilation from dominant westerly breezes. Also, a full-size louvered door is located in the ceiling of the main floor to let out hot air during warmer days. All rooms in the building have operable transoms to encourage airflow even when interior doors are closed.

The building features very heavy insulation, with a rating of R-45 for the ceiling and R-30 in the walls. Windows on the north and south façade feature shading devices, to help reduce solar gains. To further reduce energy consumption and internal loads, natural daylighting is abundant through the use of reflective light pans. The main floor features a fairly light thermal structure that includes plaster and rock pin. The majority of the building's mass is found in the basement and is in the form of concrete and masonry. The total annual utility bill runs around $1,000 for a space of 5,600 square feet. The building does not burn any fossil fuels.

2.2 Building Details

2.2.1 Lighting, Building Materials, and Heat Loads

The use of natural daylighting precludes the need for artificial lighting in most cases. On the weekends, all lighting in the assembly room may be turned on because of a monthly-changing art display. This represents the most significant source of internal heat. On cloudy days, full-time workers may turn on individual incandescent desk lamps (60 W). Indirect lighting by 40 W fluorescent tubes is also available. A summary of lighting is included as follows:

Location	Quantity	Description
Assembly Room	16	50 W ceiling mounted spots
	8	120 W ceiling mounted spots
	20	40 W ceiling globe bulbs
	6	40 W fluorescent tubes
Conference Room	6	40 W fluorescent tubes
Central Lobby	10	40 W fluorescent tubes
Admissions	10	40 W fluorescent tubes
	2	60 W ceiling mounted spots
Assorted	4	60 W incandescent desk lamps

Table 2 Lighting summary.

Since the Broadmoor center is a mixed-use building, internal heat loads from appliances and other devices are not a main issue. On the main floor, there are four computers with monitors, a small desktop copying machine, and a fax machine. In the basement, there is a stove, several computers with a monitor (running servers), two refrigerators (one full-size, one small), and smaller electrical devices.

The majority of fenestration is located on the south façade. There are a total of eight operable windows on the north. There are no windows on the east, two operable windows on the west with additional fenestration in the west entrance doors, and two operable windows on the south. There are also several inoperable daylighting windows, three windows obstructed by a trombe wall, two glass doors, and a window viewing area of the sunspace, on the south. The areas of fenestration are found in Appendix E.

As stated earlier, insulation is very heavy. The reason for this is to provide maximum efficiency for passive solar heating during the winter. The wall material from outside to inside consists of: cedar shingles, Tyvek house wrap, old barn boards with 2 x 4 stud wall, six-inch fiberglass insulation, one-inch polyisocyanurate foam board (R-7), vapor barrier, one-inch rigid-board insulation, and ¾ inch gypsum board with a skim coat of plaster.

2.2.2 Weather

Weather data from the Northeast Regional Climate Center of the National Oceanic and Atmospheric Association (NOAA) is presented in the following graphs [NOAA Boston, 2002]. All data is based on twenty-year data taken from Boston's Logan International Airport. The data reveals suitability for natural ventilation for the majority of the year.

For temperature, July's averaged daily maximum temperature rarely exceeds 80°F (26.7°C). For the most part, the monthly averaged maximum daily temperature remains below 75°F (24°C), 75% of the year. If we look at the average daily temperature, we see that for all months, the temperature remains below 75°F. ASHRAE 2% cooling design conditions for Boston indicate temperatures of 29°C db, and 21°C mwb [ASHRAE, 1997].

In Figure 77 below, we see that Boston is a climate dominated by the need for heating. In effect, there is little need for air-conditioning, particularly in a building the size of Broadmoor. The demand for heating explains why the most noticed feature of Broadmoor is passive solar heating. In an effort to retain warmth in the building, insulation in the walls and roof is significantly higher than in any typical commercial or residential construction.

In Figure 78 below, we see that relative humidity can be very high during the morning. Yet, during the summer, this is also when the dry bulb temperature will be lower and within thermal comfort ranges.

In Figure 79, we see that from May to November, winds predominantly come from the southwest. During all other months, the dominant direction is from the northwest. Average velocities are around 12 miles per hour (5.4 m/s).

In Figure 80, we see that, for the most part, there is usually some form of cloud cover over the Boston area for the majority of the year. In any given month, the percentage of sunshine is around 60-70%. These values become important in determining how important solar radiation is to building thermal dynamics.

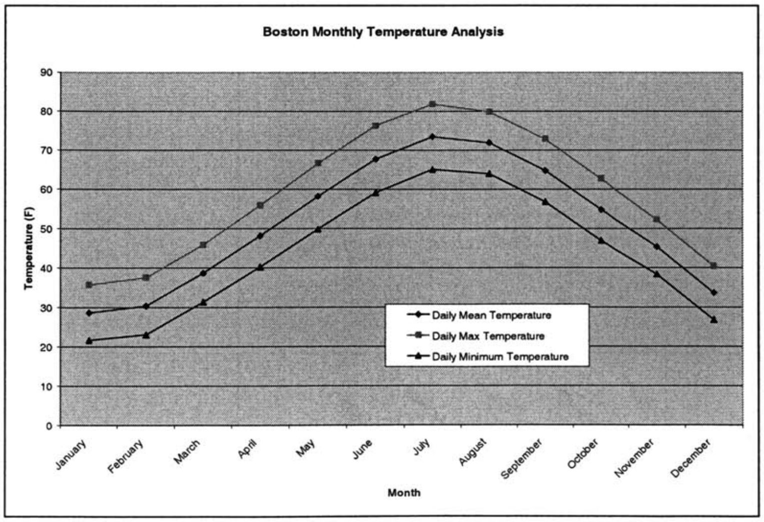


Figure 76 Monthly average mean, average maximum, and average minimum temperature for Boston, Massachusetts.

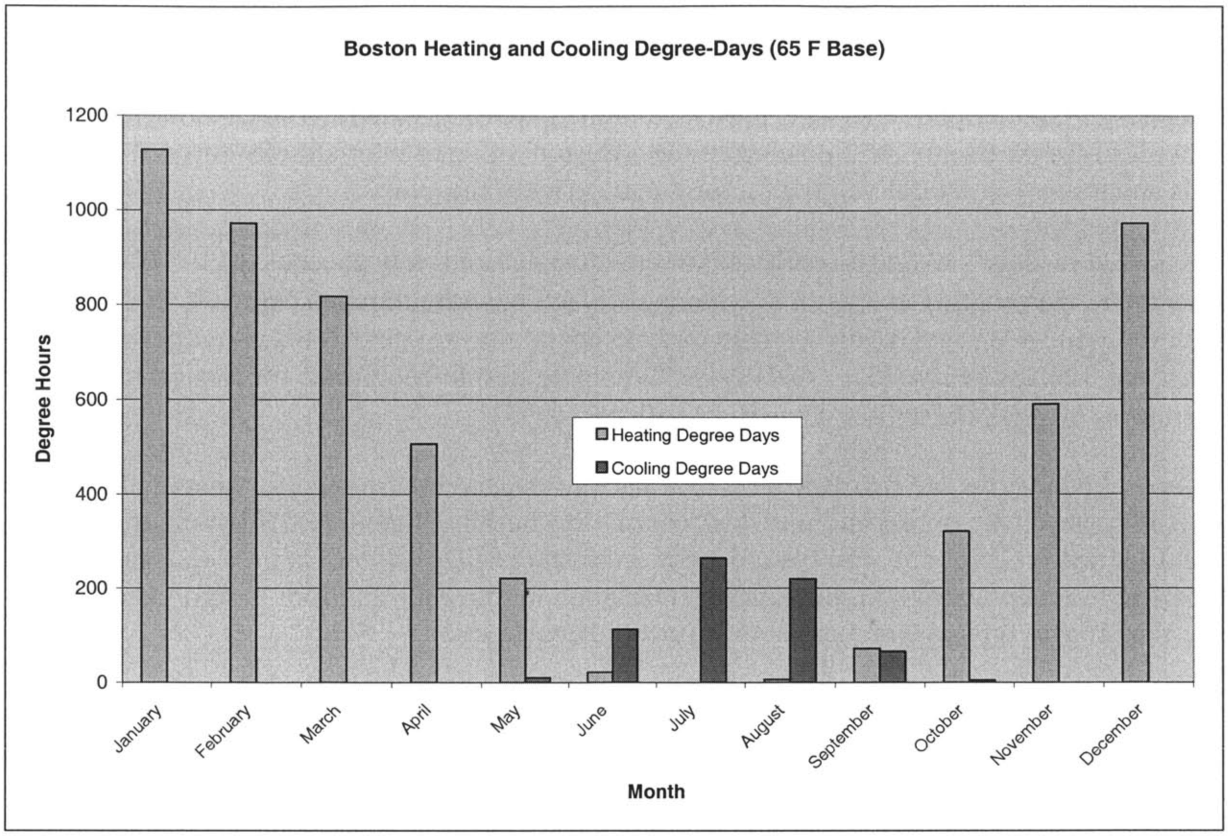


Figure 77 Monthly degree-day data. The data is based on a 65°F (18.3°C) balance point temperature.

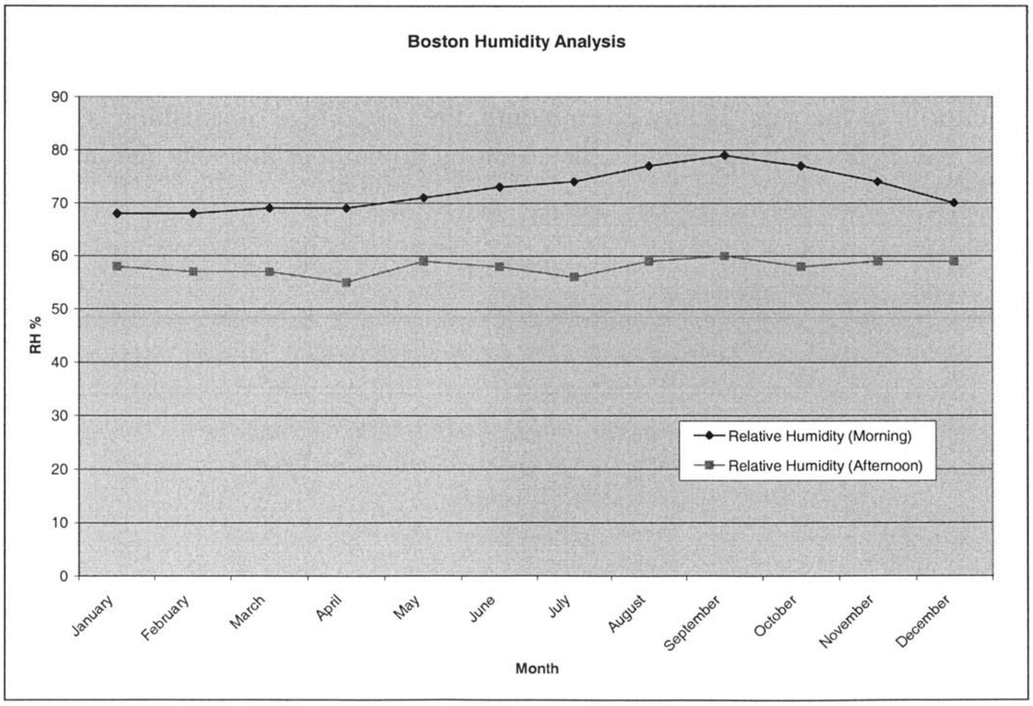


Figure 78 Average monthly morning and afternoon relative humidity.

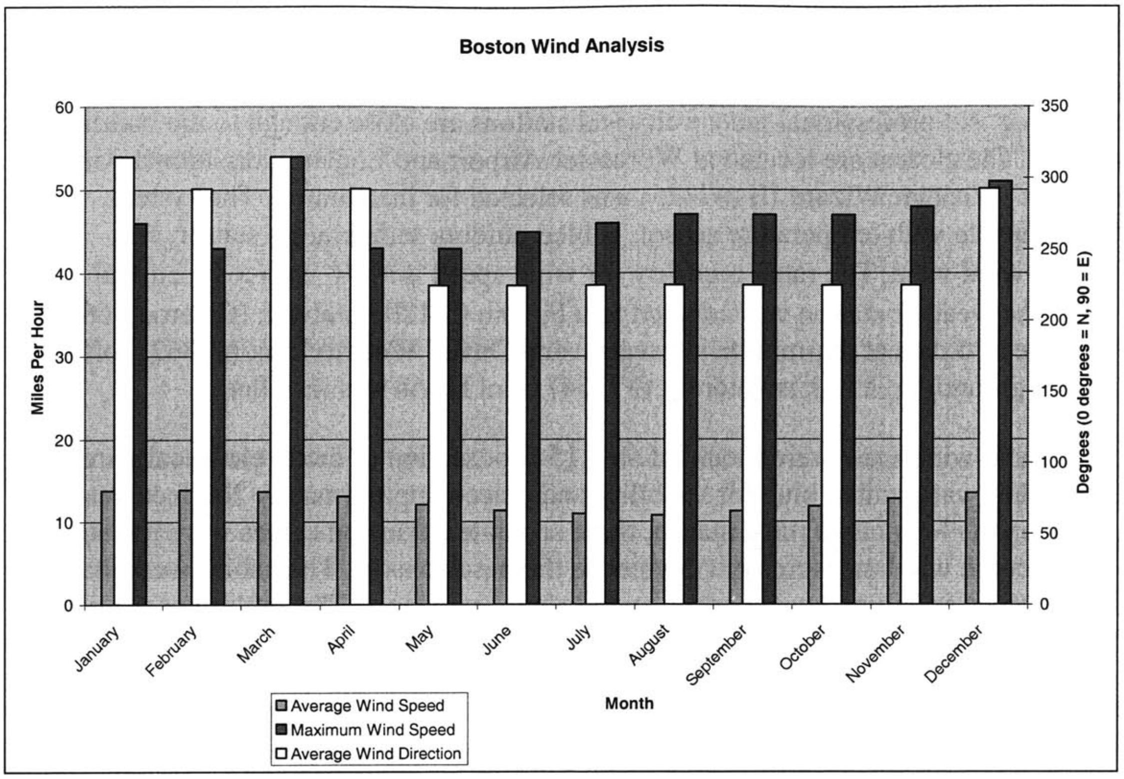


Figure 79 Average and maximum wind speed and average wind direction.

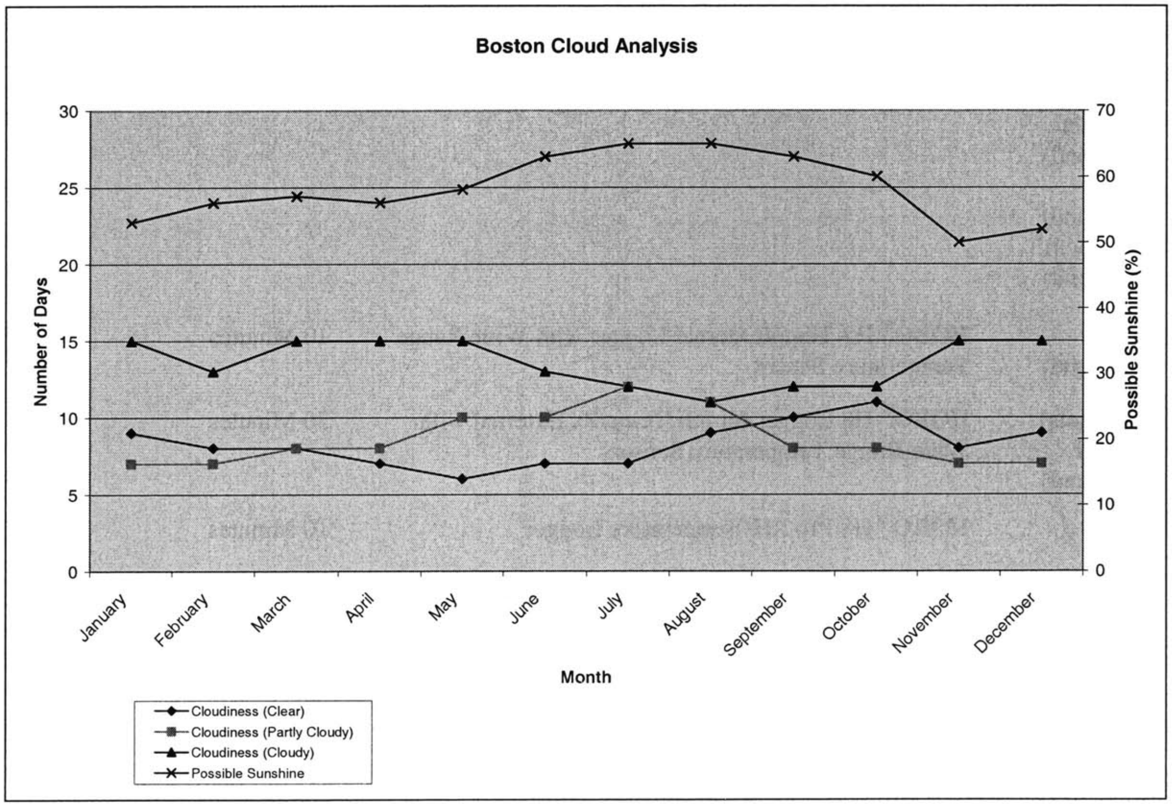


Figure 80 Cloud and sunshine analysis.

2.3 Long Term Instrumentation

An analysis of the building site indicated that a weather station should be placed in the open field west of the building. No professional meteorological stations are close enough to the building to use as substitutes. The closest are located at Worcester Airport and Logan International Airport. Davis Instruments' Weather Wizard III (#7425) was selected for installation. The system includes a base console with temperature sensor, cabled outdoor temperature sensor, cup anemometer, and wind vane. The rated accuracy for wind speed is ± 5% with a directional accuracy of 7°. The weather station was coupled to a Fujitsu C4120 notebook (Celeron 366 Mhz, 64MB RAM) to record data at ten-minute intervals using Davis' WeatherLink (#7862) software. To ensure proper grounding, a link isolator kit (#7764) from Davis was installed.

The anemometer and wind vane were mounted on a 15-foot section of metal electrical wire conduit. The conduit was painted blue for visibility and placed approximately 200 feet west of the building. Given the long cable run distance, three separate extension cables were joined together to connect the wind measurement devices to the base console. The cables were marked in yellow for visibility and joined using crimp style splice connectors. The cables consist of 4 individual 22-gauge wires (same as used in telephone cables).

The main floor of the building became the focus of the study. Four HOBO temperature loggers from Onset Computer Corporation were deployed on this floor. Additional loggers were deployed in the attic, as well as in the basement. The loggers will be left for an indefinite period of time. The loggers used are summarized in the following table:

Location	Part Type	Logging Interval
Lobby (7 feet off ground) Assembly Room (7 feet off ground) Basement (7 feet off ground) Conference Room (6 feet off ground)	HOBO® H8 Temp/External Logger w/ High Accuracy Temperature Sensor	10 minutes
Closed Office (6 feet off ground)	HOBO® H8 Temp/External Logger with Wide Range Temperature Sensor	10 Minutes
Attic (Two Points) Main Floor RH (7 feet off ground)	HOBO® H8 Logger for RH/Temp/2x External with Wide-Range Temperature Sensors	30 Minutes
Outside	HOBO® H8 Pro RH/Temperature Logger	10 Minutes

Table 3 Logger placement.

2.3.1 Detailed Logger Description

Four types of loggers from Onset Computer Corporation were used. Data from the loggers is downloaded to a laptop computer using Boxcar Pro 4.0 software. A HOBO Shuttle or serial cable is used to move data from each logger to the computer. The HOBO Shuttle is a small device that allows downloading of data without the need to bring a laptop to the location where a particular logger is placed.

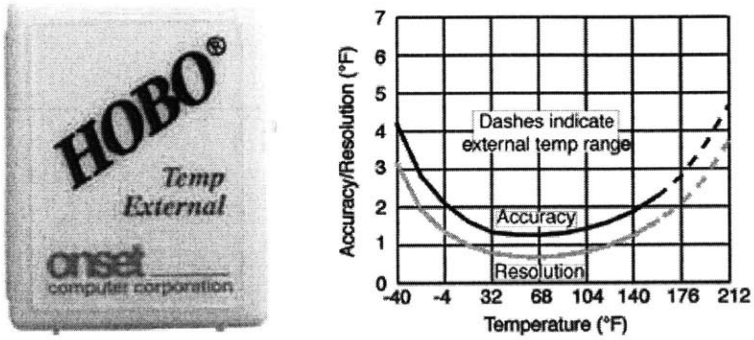


Figure 81 HOBO Temp/External Logger.

Model Number	H08-002-02
Capacity	7,943 Measurements
Range	Sensor inside case: -4°F to +158°F (-20°C to +70°C) Sensor outside case: -40°F to +248°F (-40°C to +120°C)
Accuracy	±1.27°F (±0.7°C) at +70°F
Resolution	0.7°F (0.4°C) at +70°F
Response time still in air	15 min. typical with sensor inside case; 1 min. typical with sensor outside case
Logging Interval	0.5 seconds to 9 hours
Time Accuracy	±1 minute per week at +68°F (+20°C)

Table 4 HOBO Temp/External logger specifications.

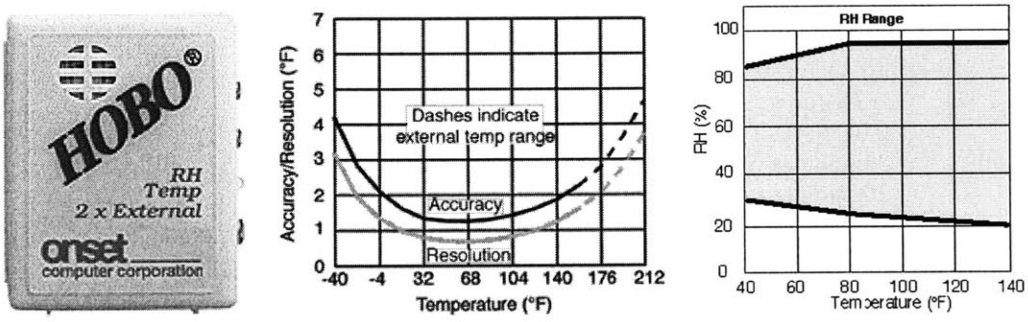


Figure 82 HOBO Logger for RH/Temp/2x External

Model Number	H08-007-02
Capacity	7,943 Measurements
Range	Sensor inside case: -4°F to +158°F (-20°C to +70°C) Sensor outside case: -40°F to +248°F (-40°C to +120°C) RH: 25% to 95% RH at +80°F for intervals of ≥ 10 seconds, non-condensing and non-fogging
Accuracy	±1.27°F (±0.7°C) at +70°F; ±5% (RH)
Resolution	0.7°F (0.4°C) at +70°F
Response time still in air	15 min. typical with sensor inside case (Temp); 1 min. typical with sensor outside case (Temp) 10 min. typical in air (RH)
Logging Interval	0.5 seconds to 9 hours
Time Accuracy	±1 minute per week at +68°F (+20°C)

Table 5 HOBO Logger for RH/Temp/2x External specifications.

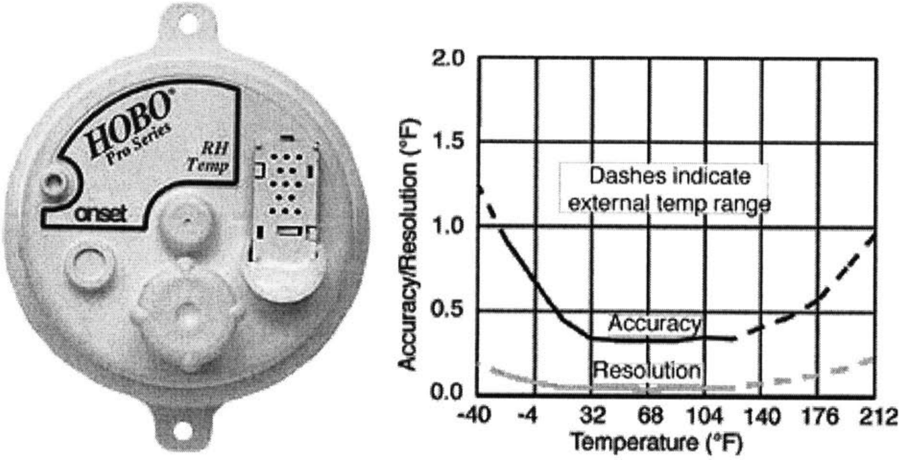


Figure 83 HOBO Pro RH/Temperature logger.

Model Number	H08-032-08
Capacity	32,645 High-Resolution Measurements
Range	-22°F to +122°F (-30°C to +50°C) RH: 0% 100% RH
Accuracy	±0.33°F (±0.2°C) at +70°F in high resolution mode ±3% (up to ±4% in condensing environments)
Resolution	0.04°F (0.02°C) at +70°F in high resolution mode
Response time still in air	34 minutes typical 30 minutes typical in still air (RH)
Logging Interval	0.5 seconds to 9 hours
Time Accuracy	±1 minute per week at +68°F (+20°C)

Table 6 HOBO Pro RH/Temperature logger specifications.

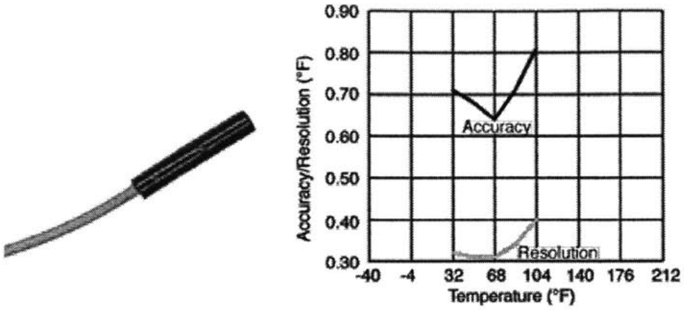


Figure 84 High-accuracy temperature sensor.

Model Number	TMC6-HB
Dimensions	6 foot cable; 0.3" diameter sensor
Range	+32°F to +110°F (0°C to +44°C) in air
Accuracy	±0.7°F at +70°F (±0.4°C at +20°C
Resolution	0.3°F at +70°F (0.2°C at +20°C)
Response time still in air	7.5 minutes in still air

Table 7 High-accuracy temperature sensor specifications.

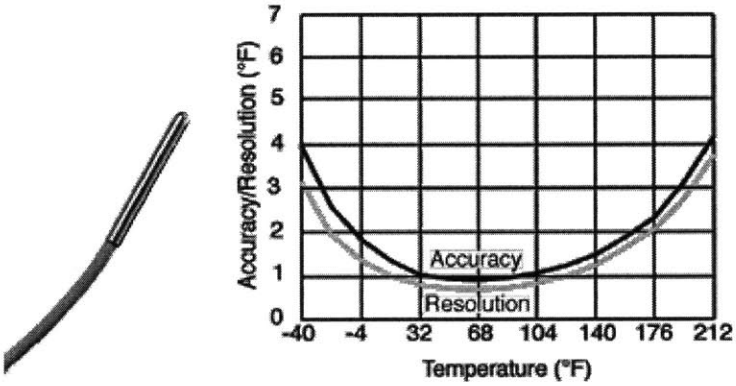


Figure 85 Wide-range temperature sensor.

Model Number	TMC20-HA
Dimensions	20 foot cable; 0.2" diameter sensor
Range	-40°F to +212°F (-40°C to +100°C) in air
Accuracy	±0.9°F at +70°F (±0.5°C at +20°C)
Resolution	±0.7°F at +70°F, (±0.41°C at +20°C)
Response time still in air	4.5 minute typical

Table 8 Wide-range temperature sensor specifications.

Temperature sensors were mounted to wooden dowels for additional stability and visibility. The sensors were coated with a thin-layer of aluminum reflective paint, to reduce errors from solar radiation. While the paint likely reduced response time, a collection interval of ten minutes, should be sufficient.

2.4 Building Diagrams and Pictures

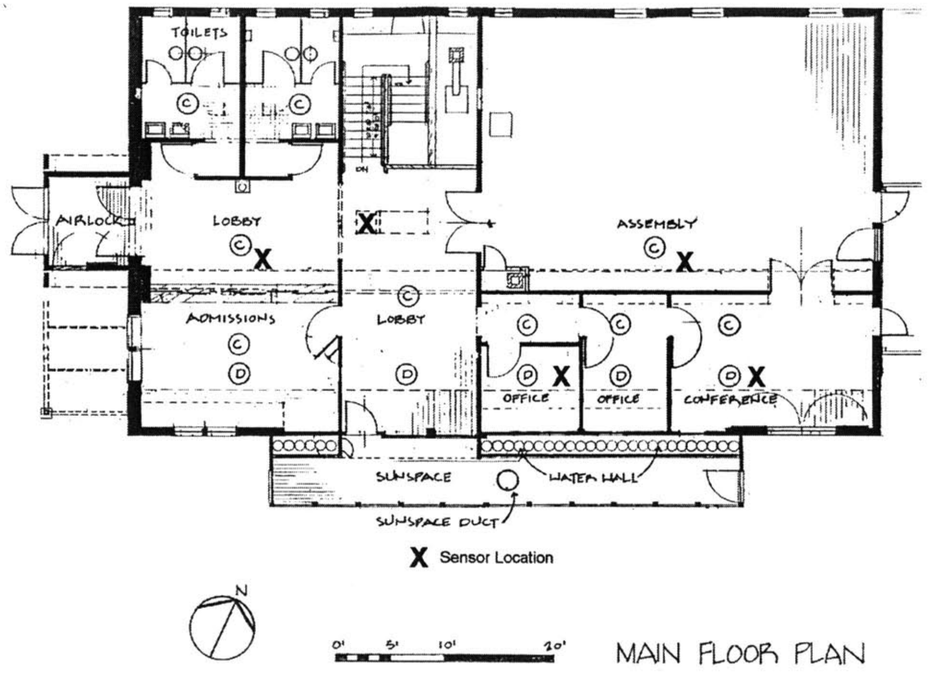


Figure 86 Main floor plan. Sensors were placed in four locations on this floor. There is also a sensor located above the stack vent and another one in the basement. Sensors were mounted so as not to be obtrusive, given the large number of children that enter and exit the building on a daily basis. Diagram courtesy of Ives' Architects.

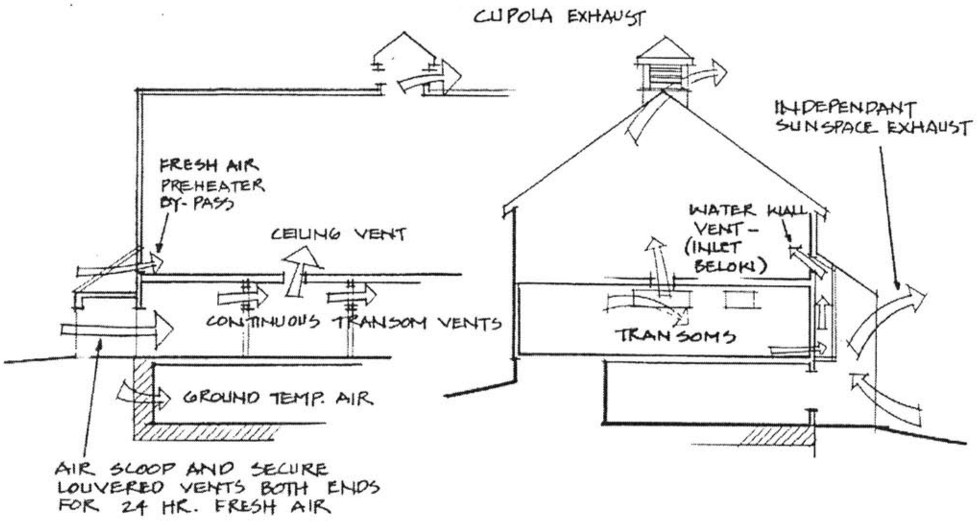


Figure 87 Building airflow diagram. During the summer, breezes come primarily from the west, driving air through the louvered doors as shown in this diagram. When there is little wind, warm air rises into the attic and out the cupola on the roof. Diagram courtesy of Ives' Architects.

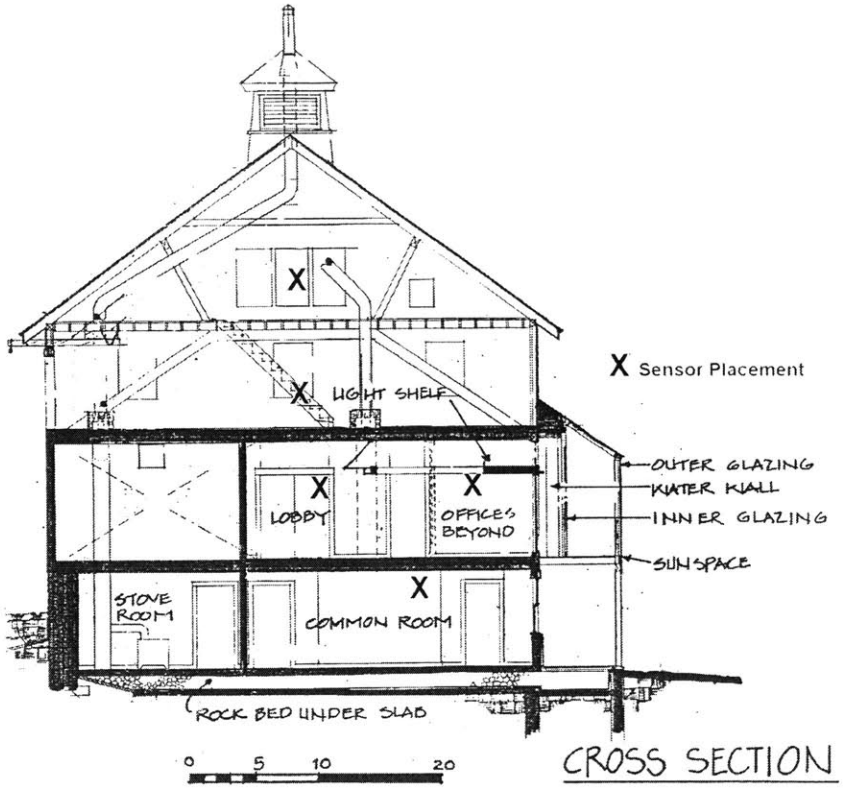


Figure 88 Cross-section. Note the two attic levels. The first attic level remains at cooler temperatures during the summer than the upper attic level. The upper level is often used to dry leaves and herbs because of this. During the summer, hot air from the passive solar space exhausts into the attic. Diagram courtesy of Ives' Architects.

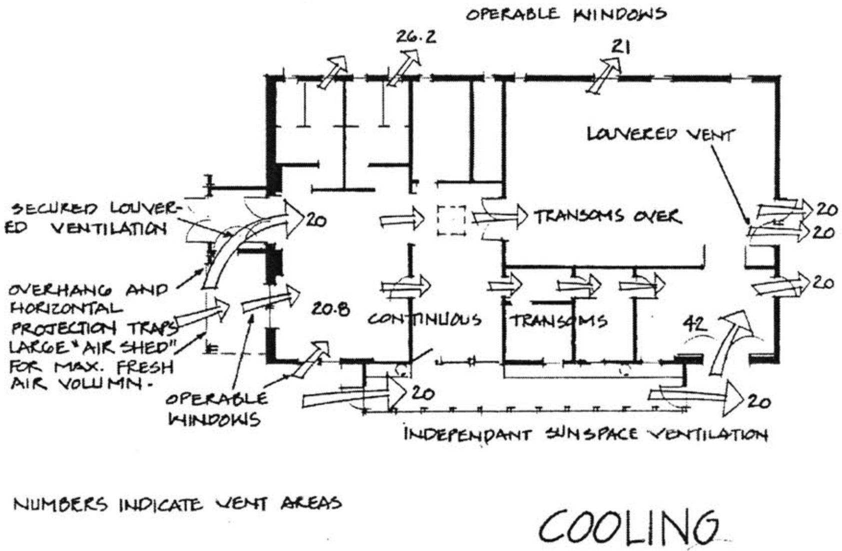


Figure 89 Cooling diagram. Vent areas are given in square feet. Transoms throughout the building allow air to pass freely. Operable windows are triple-glazed and argon filled. Diagram courtesy of Ives' Architects.

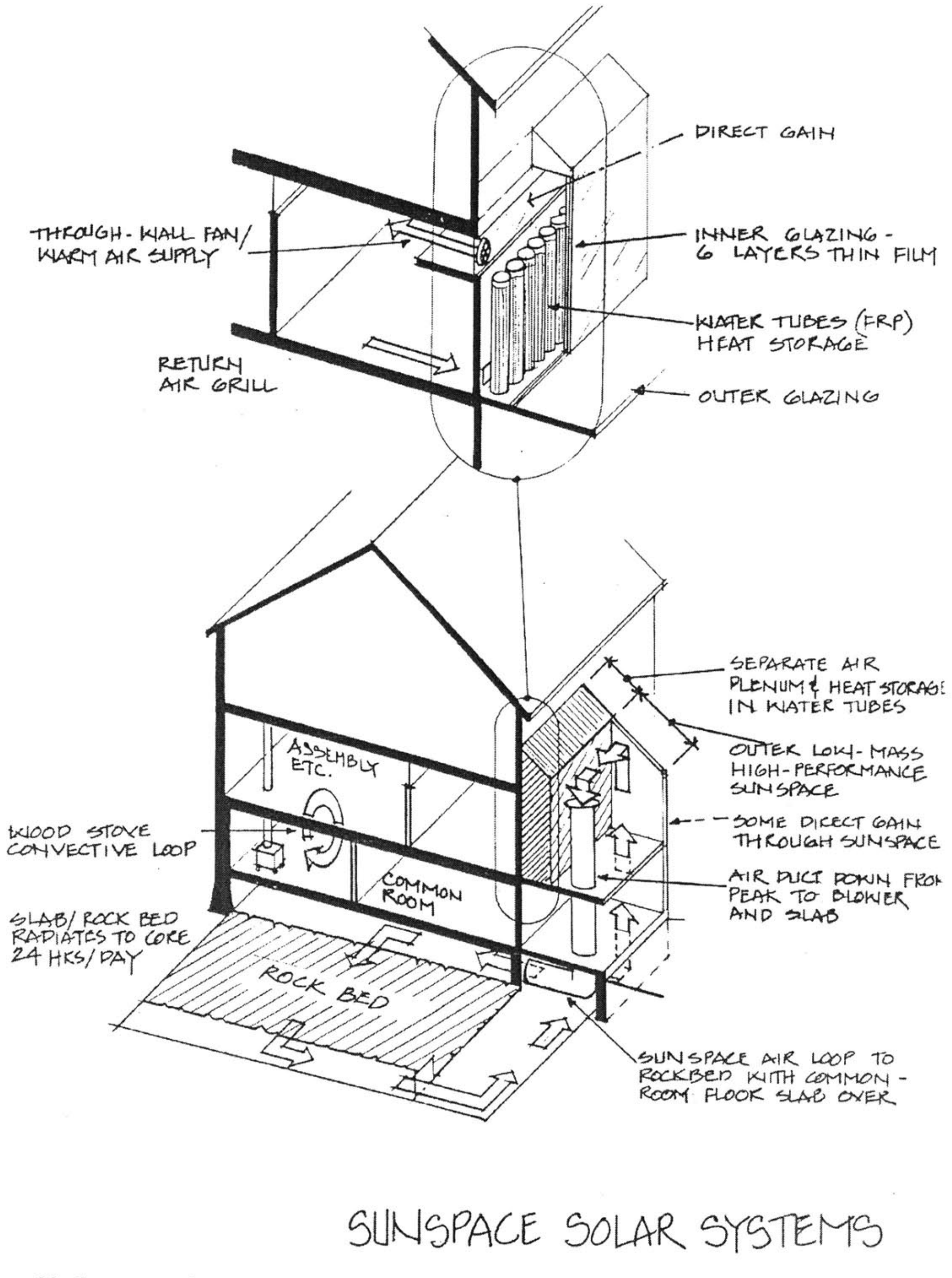


Figure 90 Sunspace solar systems. While the sunspace does not aid in cooling, it is still very much part of the year-round energy efficient ventilation strategy of the building. There is thought of somehow reversing the system to work in summer cooling. Diagram courtesy of Ives' Architects.

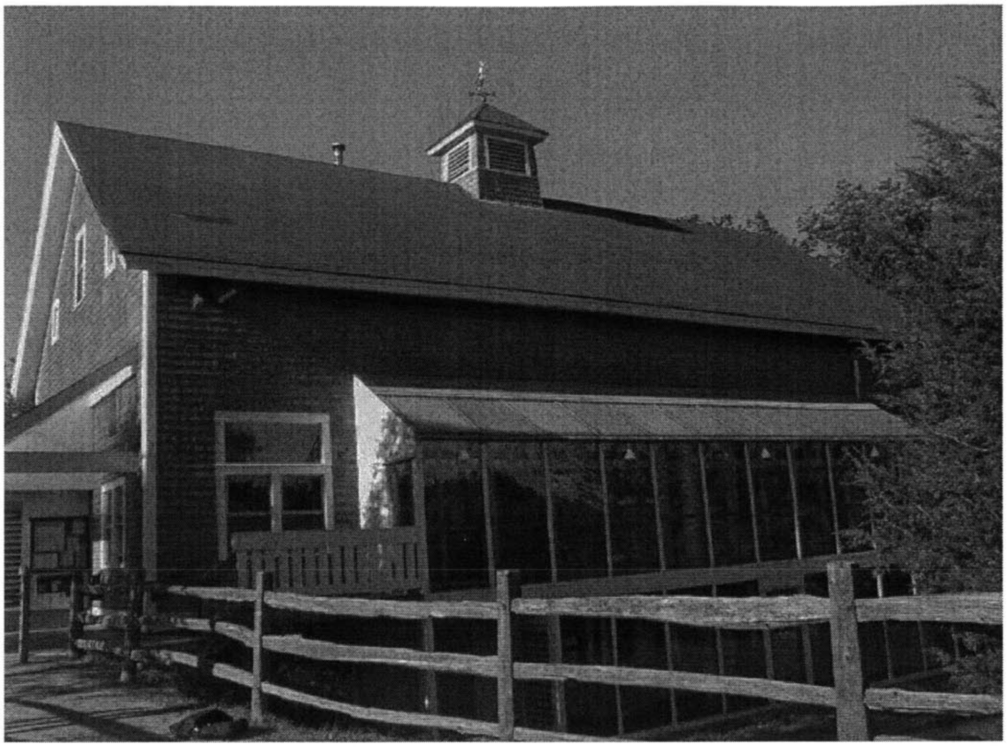


Figure 91 South façade. The glass enclosure retains heat during the winter. It is ventilated during the summer through use of two full-size doors. The cupola on the roof allows hot air to exhaust from the attic spaces.

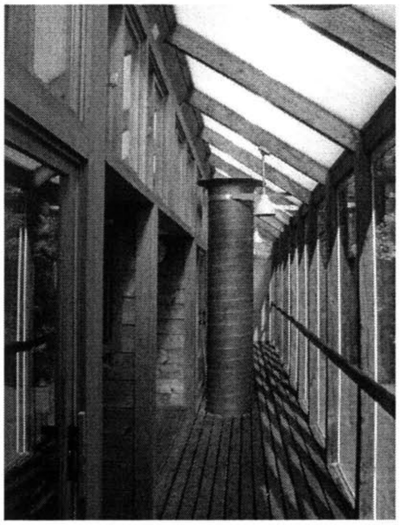


Figure 92 Interior of sunspace. The metal cylinder draws air from the sunspace during the winter to heat the floor slab in the basement.

Figure 93 Sunspace fan housing. The fan draws air from the sunspace into the bedrock underneath the concrete basement floor slab.

Figure 94 Basement common area. This space is used often during the summer because of the high availability of thermal mass.

Figure 95 West façade from open field.

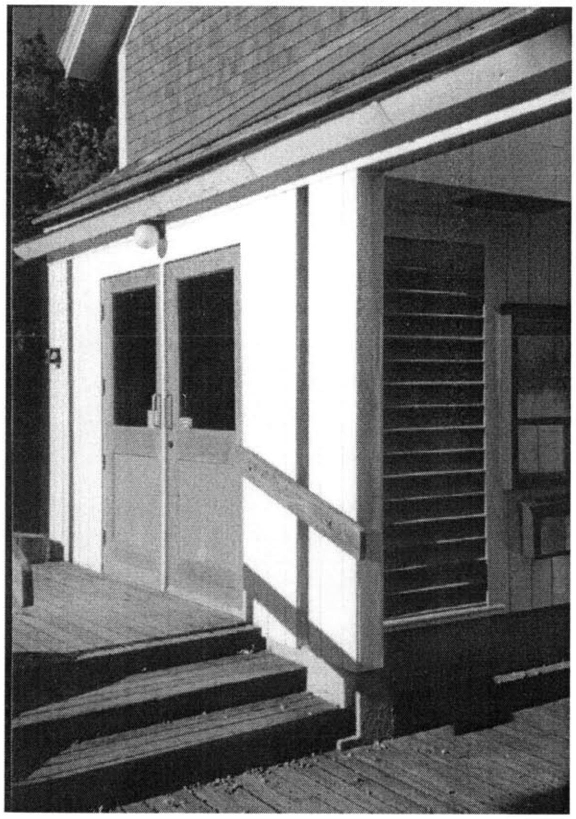


Figure 96 West entryway. The louvered door on the right allows outdoor air to flow into the building at all times.

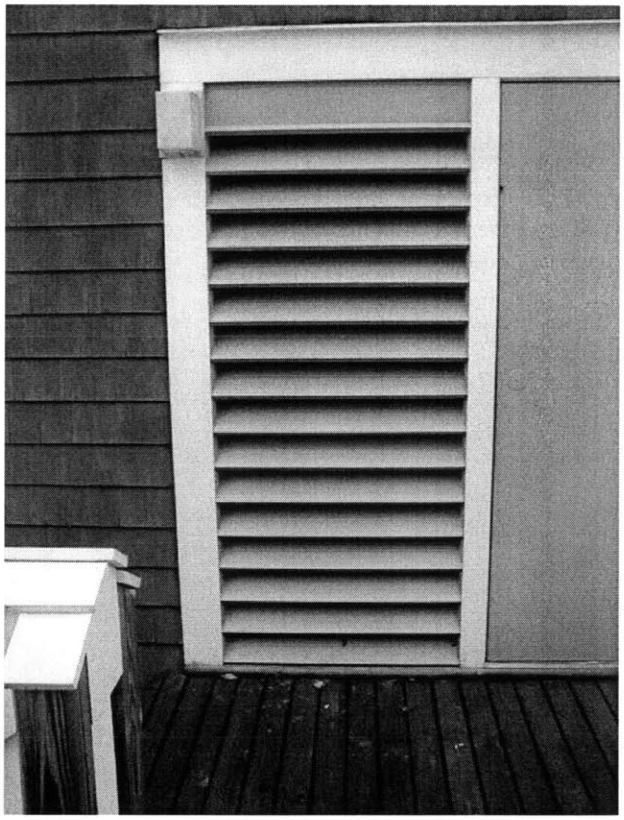


Figure 97 East louvered door. This door, open in conjunction with the west louvered door, allows for cross ventilation twenty-four hours a day.

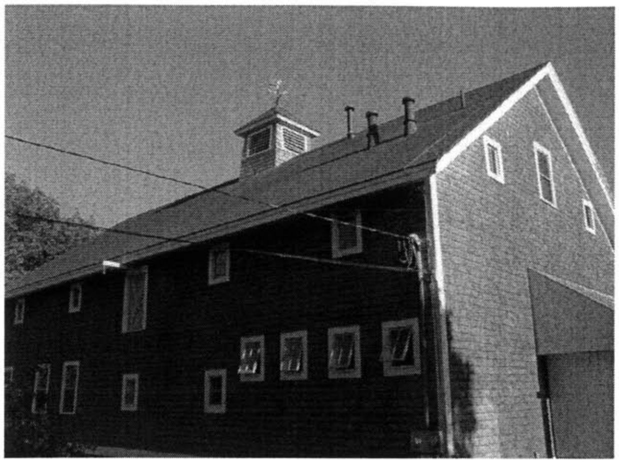


Figure 98 North façade. The open windows ventilate the bathrooms.

Figure 99 Assembly room. This space is used for assorted events, with a peak capacity of up to 60 persons. A monthly changing art exhibit is featured on the walls.

Figure 100 Southeast corner. Note the overhang on the west façade, which provides sun shading. The overhang was also designed to channel wind into the building. Also, note the louvered door for night ventilation.

Figure 101 Art exhibit. The portion above the artwork is clear to allow daylight to penetrate from the south.

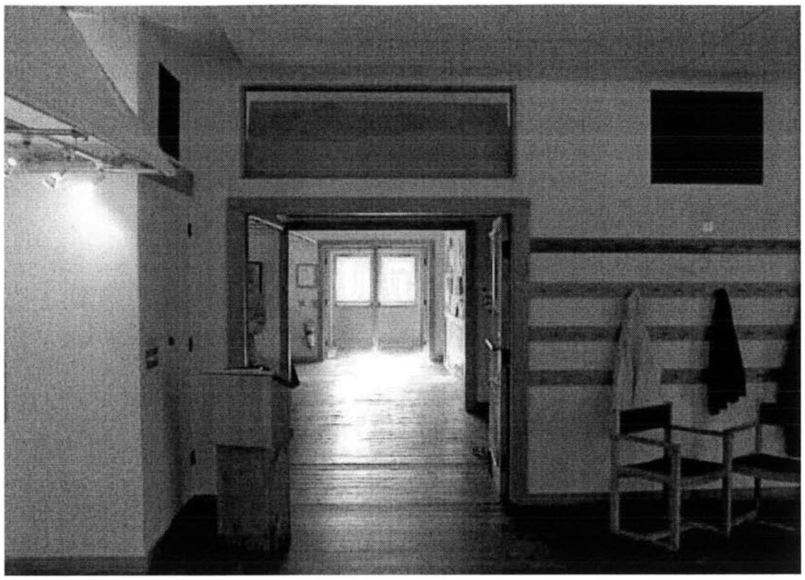


Figure 102 Corridor from assembly room. Several transoms, like the one in this picture, allow air to pass through the building even when doors are shut for noise control.

Figure 103 Conference room. Note the amount of natural daylight cast on the walls and ceiling of the space. A reflective fabric in the light pan bounces light from the upper windows onto the ceiling, to minimize artificial lighting requirements.

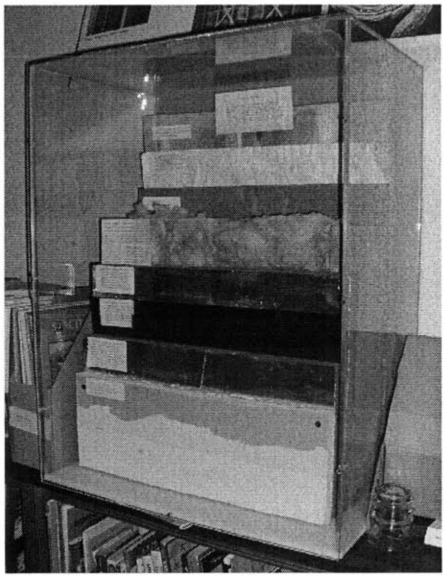


Figure 104 Wall cross-section. The wall features several layers of insulation for a combined wall resistance value of R-30 (R-40 in the ceilings).

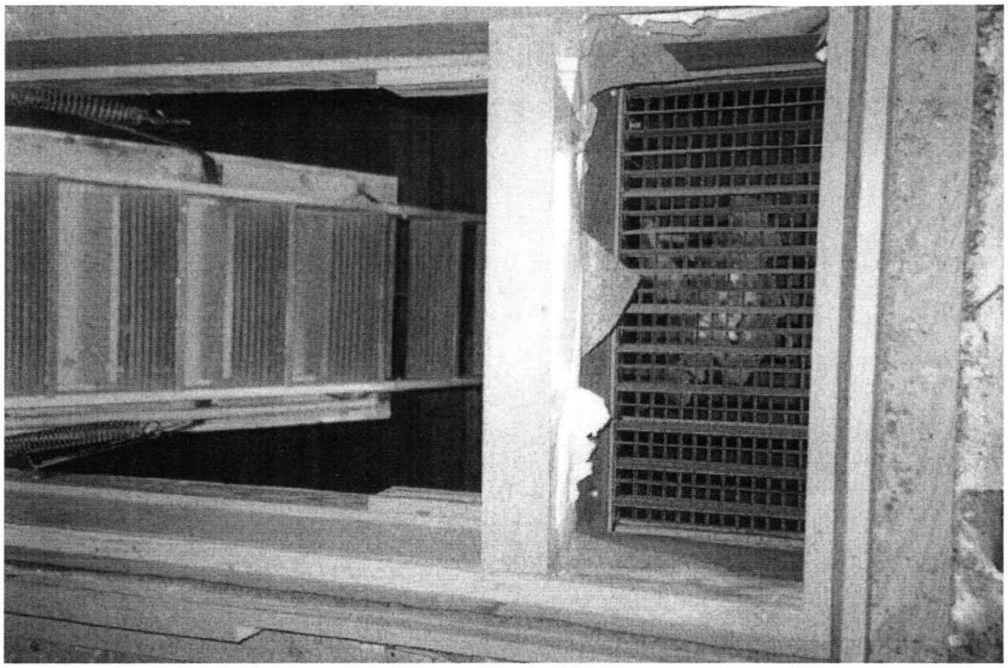


Figure 105 Stack vent. The staircase to the left is typically in a folded position, leaving the vent on the right as the sole means for warm air to rise into the attic.

Figure 106 Attic door. This door is closed during the heating season. It is left open at all other times to let warm air to rise into the attic.

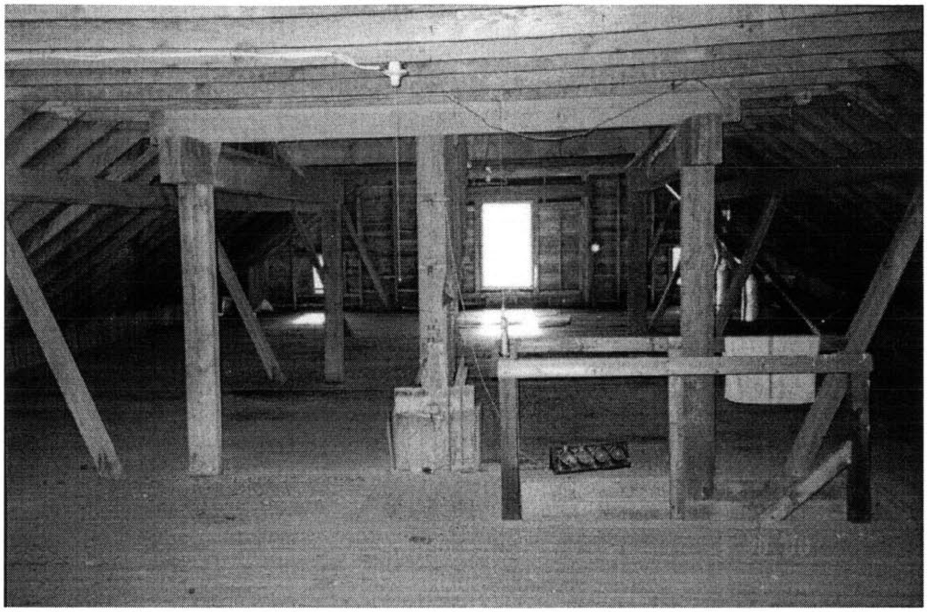


Figure 107 Attic space. The attic consists of two levels. Cracks in the wood between the first and second levels allow air to circulate throughout the space. Several windows in this space are opened during the cooling season to ventilate the space and prevent it from reaching extreme temperatures.

Figure 108 Open field. The weather station's anemometer and wind vane are located in this field, approximately 200 feet from the building. This field is the most open area surrounding the building.

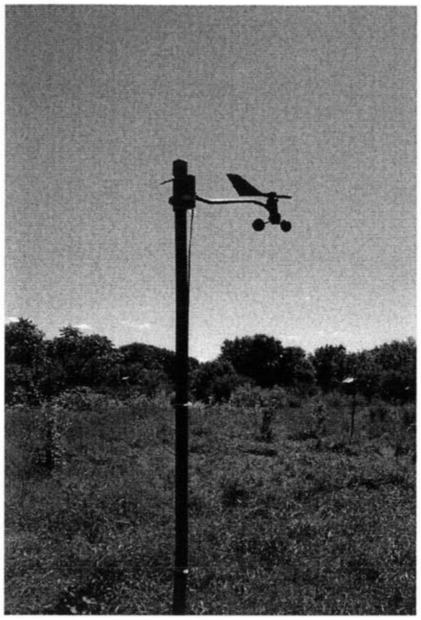


Figure 109 Wind monitoring instruments. A wire runs from the instruments to a laptop in the attic of the building.

Figure 110 Open field. This field is located west of the building. The wind station is located approximately in the center of the picture.

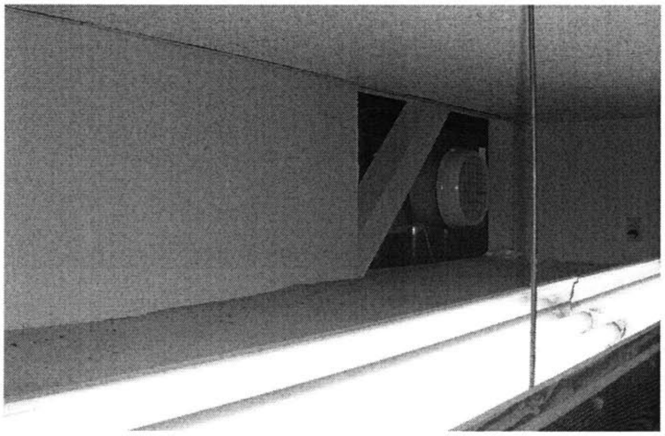


Figure 111 Reflective light pan. A pan that extends out along the entire length of the south wall reflects light onto the ceiling. The material in the pan is a silver-colored reflective cloth. The fan in the back brings warm air from the sunspace into the conference room. Fluorescent lamps along the front edge of the pan are used when there is little sunshine.

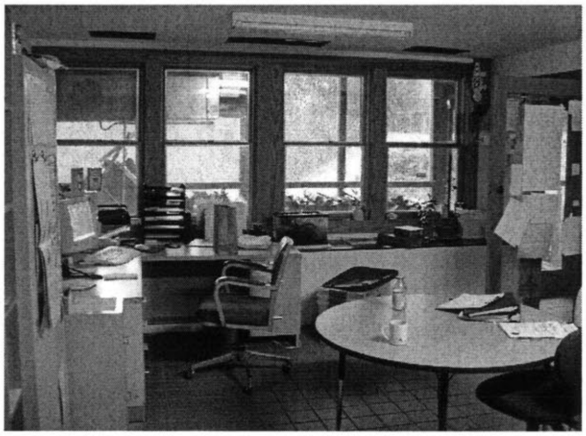


Figure 112 Basement office. The black vents in the ceiling allow air from both floors to mix with each other during winter heating, for better temperature distribution.

2.5 Sensor Mounting Pictures

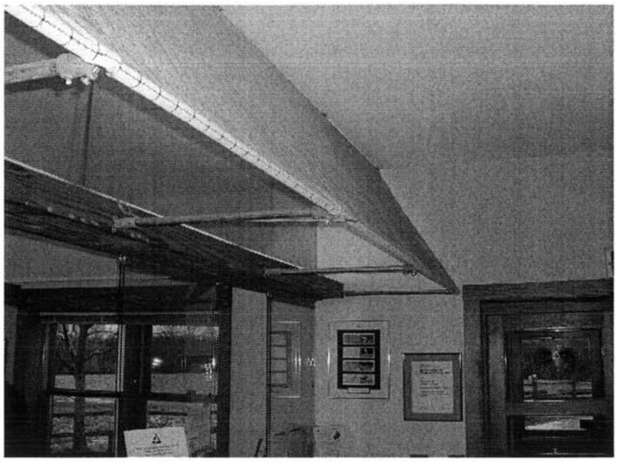


Figure 113a Lobby temperature sensor.

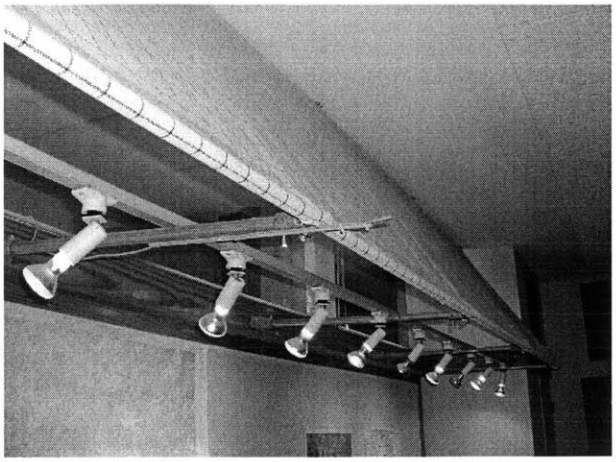


Figure 113b Assembly room temperature sensor.

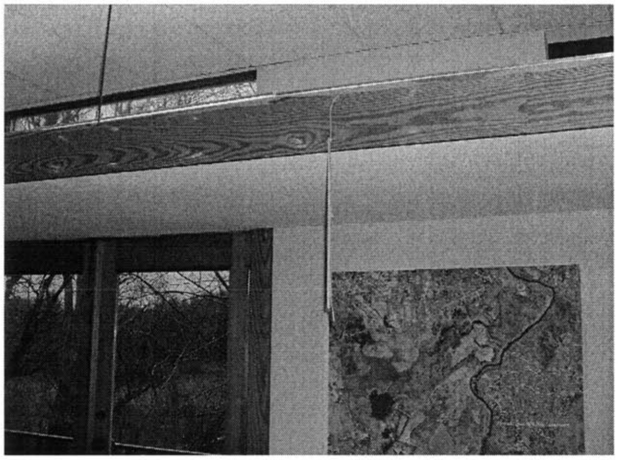


Figure 113c Conference room temperature sensor. The overhang is a reflective light pan.

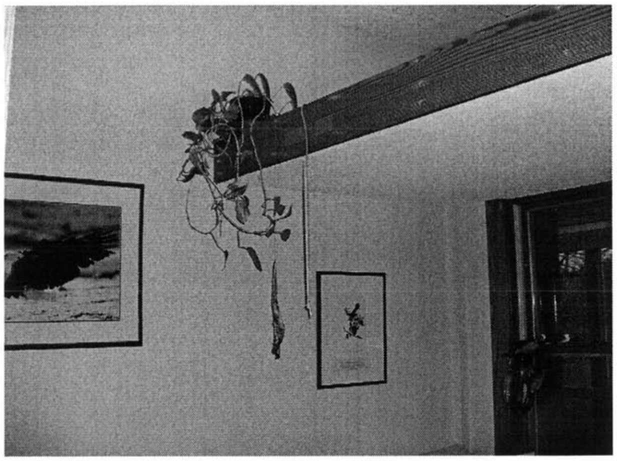


Figure 113d Isolated office temperature sensor.

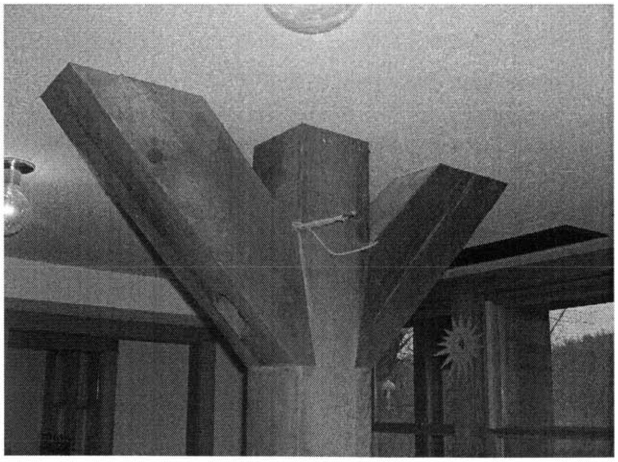


Figure 113e Basement temperature sensor.

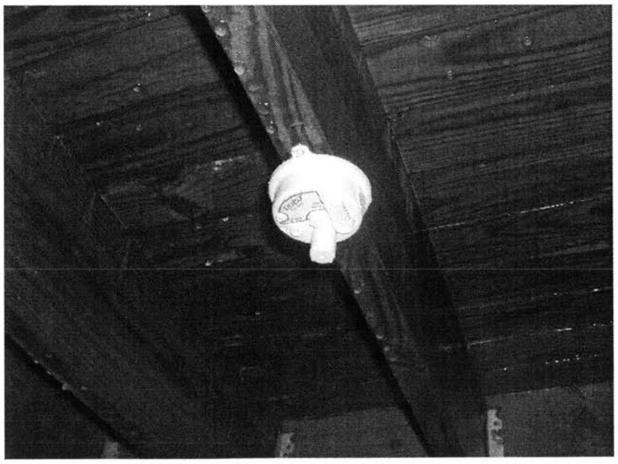


Figure 113f Outdoor temperature sensor located east of building underneath a staircase.

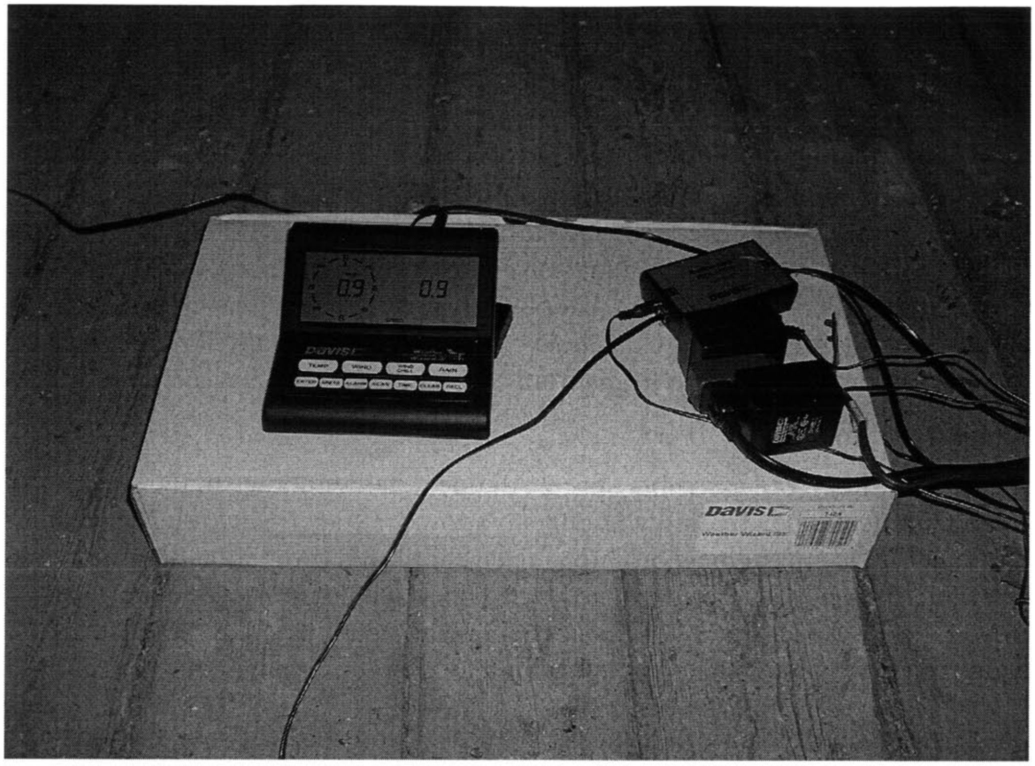


Figure 114 Weather station equipment. The device on the left is the weather station console. The device on the top right is a link isolator, which ensures a proper reference voltage for the wind station devices.

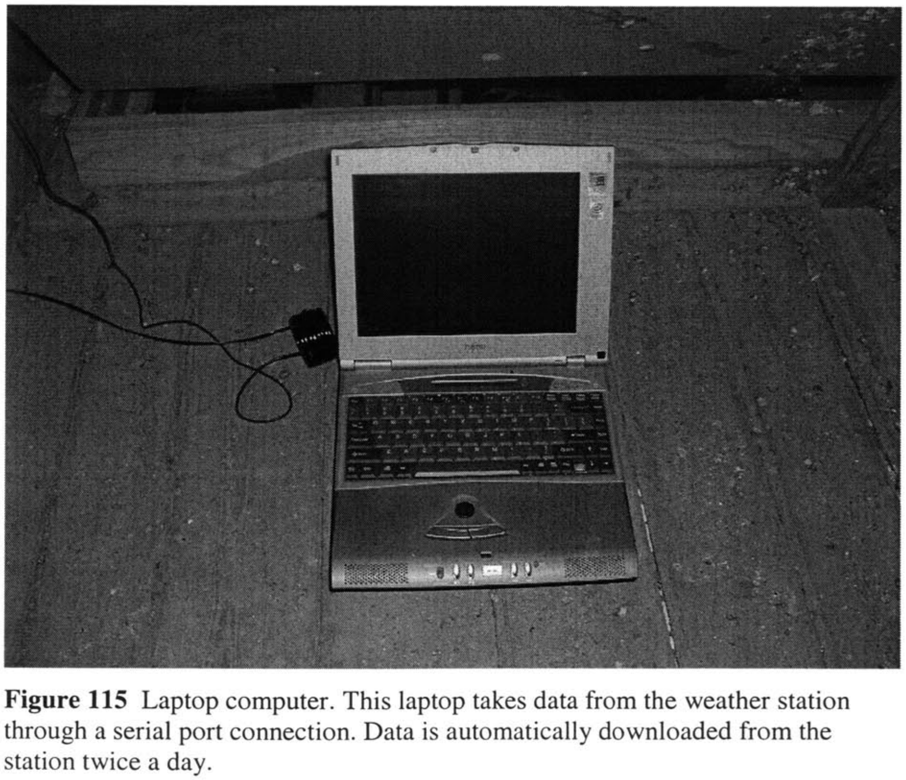


Figure 115 Laptop computer. This laptop takes data from the weather station through a serial port connection. Data is automatically downloaded from the station twice a day.

2.6 Short-Term Site Measurements

2.6.1 Tracer Gas

Given the proximity of the Broadmoor nature center to MIT, tracer gas experiments were attempted using a simple grab bottle method, as specified by ASTM standard E741 [ASTM, 1993]. 500 ml polyethylene bottles were used to bring sulfur hexafluoride (SF_6) to the test site, as well as to bring collected samples back to lab for analysis. Latex rubber balloons were placed inside several bottles and then filled with SF_6. The balloons ensured that gas was indeed filling each bottle. Each bottle featured a screw cap with a hole closed with a 3 mm thick rubber gasket. An 18-gauge syringe needle was used to sample gas from each bottle; the gasket serves as a reusable septum.

Tracer gas experiments were run in the assembly space. All doors and windows to the space were closed and sealed with duct tape. Sealing was done to allow the tracer gas to stabilize and evenly mix in the space before sampling began. Three fans were placed throughout the room to aid in mixing of the tracer gas. This occurred for one hour. The louvered door on the east wall and the double-doors on the west wall to the assembly room were then opened. Samples were taken from two locations in the room every 30 minutes for a total of 4 hours.

Samples were tested using a Brüel and Kjær Multi-gas Monitor (Type 1302). The monitor relies on the photo-acoustic infrared detection method and was used in conjunction with the Type 1309 Multipoint Sampler and a DOS-based computer running Type 7300 application software. The specifications are included in the following table:

Response Time	Tube length less than 1m, ~35 s (one gas) ~120 s (five gases)
Measurement Range	Detection Limit: typically 10^{-2} ppm to 1 ppm depending on gas Dynamic Range: 10^5 times detection limit
Accuracy-Zero Drift	Typically ± Detection limit per 3 months Influence of temperature: ±10% of detection limit/°C Influence of pressure: ±0.5% of detection limit/mbar
Accuracy-Repeatability	1% of measured value
Accuracy-Range Drift	±2.5% of measured value per 3 months Influence of temperature: ±0.3% of measured value/°C Influence of pressure: -0.01% of measured value/mbar
Volume of air required per sample	using 1 m sampling tube: 140 cm^2/sample
Data storage capacity	Sufficient for a 12-day monitoring task, monitoring 5 gases and water vapor every 10 min.

Table 9 Tracer gas monitoring equipment specifications.

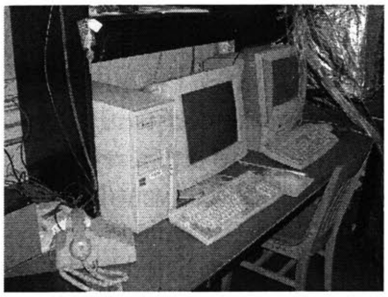


Figure 116a Tracer gas computer controller.

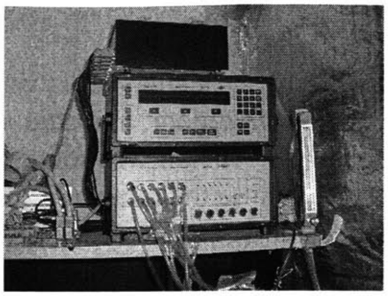


Figure 116b Tracer gas sampler and analyzer.

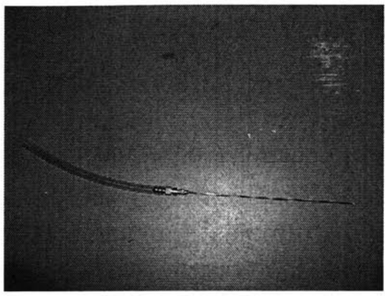


Figure 116c Gas needle.

2.6.2 Surface Temperature

A Raytek Raynger©ST6 non-contact thermometer was used to check surface temperatures throughout the building during each on-site visit. For each room, six measurements were usually taken: one for each of four walls, ceiling, and floor. This information was taken to calculate a mean radiant temperature for the space. Aiming was aided with a built-in laser pointer. The thermometer was pre-calibrated by the manufacturer. The specifications for the thermometer are included in the following table:

Temperature Range	-32 to 500°C
Accuracy	±1% of reading or ±1°C, whichever is greater @ 23°C ambient operating temperature
Repeatability	±1% of reading or ±1°C, whichever is greater
Response Time	500 mSec, 95% response
Ambient Operating Range	0 to 50 °C
Power	9V Alkaline or NiCad battery
Emissivity	Adjustable 0.3 to 1.0 (0.9 was used in experiments)
Distance to spot size (90% energy)	8:1

Table 10 Raytek non-contact thermometer specifications.

Figure 117 Raytek non-contact thermometer.

2.6.3 Air Velocity

Air velocity measurements were taken during each site visit at various locations in the building: west windows, west louvered door, east louvered door, and attic vent. Given the constantly changing air directions through windows and vents, it was sometimes difficult to attain reliable readings. Readings taken did provide insight into the relative order of magnitude of ventilation. Davis Instruments' (not same as weather station manufacturer) TA5 Air Velocity Meter was used. The anemometer was calibrated by the manufacturer. The specifications are listed in the following table:

Velocity Ranges	0 to 6000 ft/min 0 to 3000 ft/min 0 to 400 ft/min
Resolution of Velocity Readings	1 ft/min
Working Temperature Range	32-176°F
Resolution of Temperature Readings	1 °F
Velocity Accuracy at 20 °C and 1013 mb	±2% reading above 400 ft/min ±8 ft/min below 400 ft/min
Temperature Accuracy	±1°F ±1 digit
Accuracy of 0-1V output	±1% of display FSD
Memory Size	99 concurrent velocity and temperature readings
Dimensions	7.25 x 3.62 x 1.25 in.
Weight (less 4 AA batteries)	14.6 oz.

Table 11 Anemometer specifications.

2.6.4 Thermal Comfort and Building Status Measurements

Five full-time staff members work at the Broadmoor nature center. One works in the basement. One is a grounds manager. The remaining three work on the main floor of the building. The center is open six days a week (closed Mondays) from 8 am until 5 pm. Occasionally, lectures on assorted topics will be held in the evenings from 7 to 9 pm. Given the multi-purpose nature of the center, visitors trickle in and out of the space at all times during the day. Typically, a visit will last no longer than ten minutes and consist of paying an admissions fee, getting a drink of water, and going to the restrooms.

The full-time staff was asked to rate their thermal sensation according to the ASHRAE seven-point index ((+3) hot, (+2) warm, (+1) slightly warm, (0) neutral, (-1) slightly cool, (-2) cool, (-3) cold) twice a day. They were also asked to make general comments on any unusual outdoor weather, odor, noise, air velocity, or humidity conditions.

Since the building does not feature a mechanical ventilation system, it was deemed feasible to keep track of door and window operation using pencil-and-paper sheets. Workers were asked to log the operation of the west admissions room windows and the east door. During the summer, the stack vent, east louvered door, and west louvered door were kept open at all times.

Chapter 3 Philip Merrill Environmental Center Description

3.1 Building Summary

The Philip Merrill Environmental Center is located southeast of central Annapolis, Maryland (38.95°N, 76.5°W). The building opened in December of 2000 and is the main headquarters of the Chesapeake Bay Foundation (CBF), a non-profit environmental group dedicated to restoring and protecting the Chesapeake Bay and its surrounding watersheds.

The Washington DC section of the SmithGroup designed the center. The SmithGroup won the bid to work on the center by showing their commitment to attaining a Leadership in Environmental and Energy Design (LEED) Platinum rating. This was accomplished with the aid of a peer-review process spearheaded by Steven Winter Associates in Norwalk, CT.

The list of features included in the building are numerous: rainwater cisterns, composting toilets, reduction of site disturbance, natural ventilation, photovoltaic electricity generation, solar hot-water heating, geothermal heat pumps with a desiccant dehumidification system, structural insulated panels, smart parking design, certified wood, use of recycled, renewable and reused materials, transportation management, native landscape species, indoor air quality monitoring, and natural daylighting. It appears that almost every feature someone would expect to see in a "green" building was incorporated into the design.

3.2 Building Site

The building is a result of an effort to consolidate 50% of CBF staff members in one central location. An extensive search near Annapolis was conducted. The eventual site chosen is the former location of the Bay Ridge Inn. The setting is not a commercial one; the building is in the center of a residential area along the Chesapeake Bay. In fact, it was because of the strong commitment of the residents of Bay Ridge that CBF was able to build their headquarters in Bay Ridge with little trouble. Approval of zoning by the State of Maryland was swift. The site allows the CBF to demonstrate conservation techniques in an appropriate setting of nature, while also having quick access to the Bay.

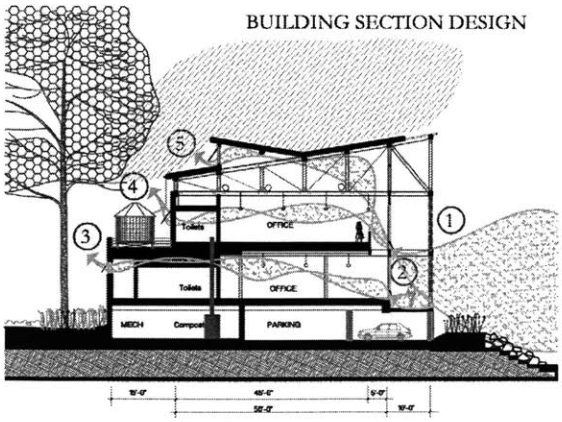


Figure 118 Diagram of intended airflow through building.

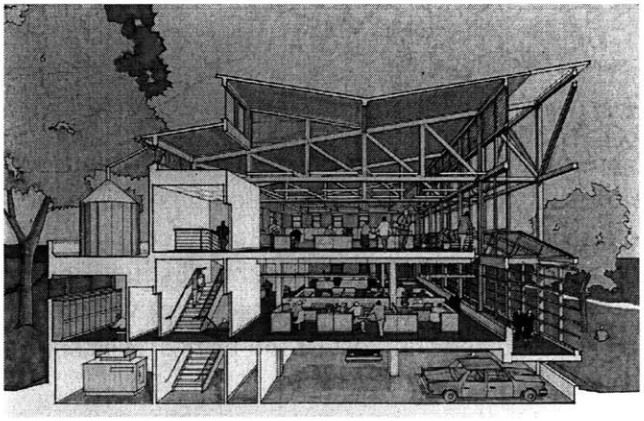


Figure 119 Illustration of building cross-section.

Pre-dominant breezes come from the south during the summer. Because the building is only a few hundred feet from the Bay, strong unobstructed breezes for natural ventilation exist.

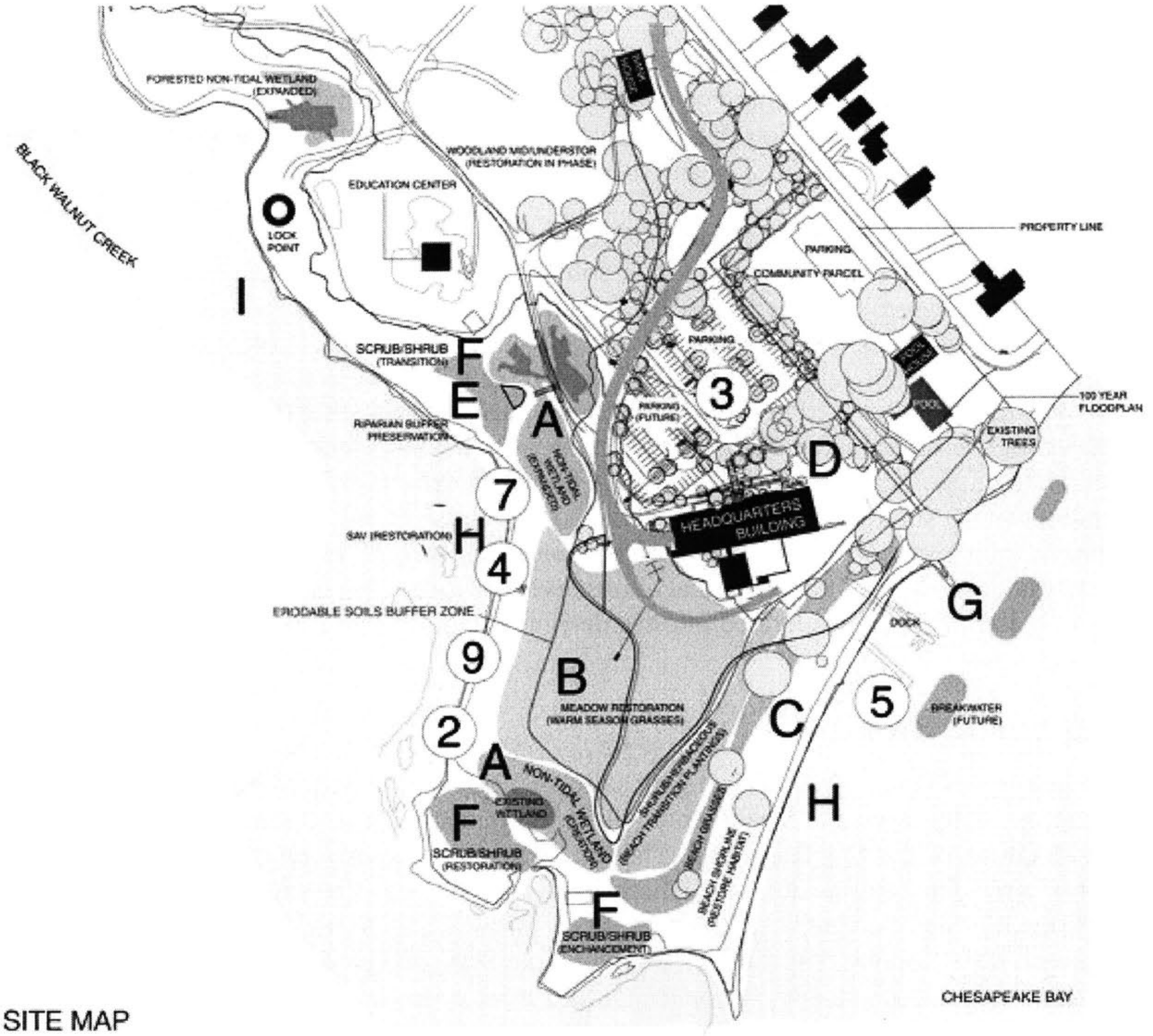


Figure 120 Site map.

3.3 Building Description

The building features two levels with a usable floor area of about 32,000 square feet (2973 m^2). The overall dimension of the building is 220 by 50 feet. The floor-to-ceiling height is 13.5 feet, with a second floor height of up to 25 feet. The building consists of three main zones: an entirely open second floor and two open, but distinct first floor areas. Approximately eighty people work in the building. Cubicle dividers are kept very low, to minimize restriction of airflow through the open spaces. The total cost of the project was six million US dollars.

Almost sixty individual controls for windows exist. Windows on the south façade are banked in groups of four and operated with hand cranks manufactured by Clearline. These cranks are mounted on the first floor of the building and are used to open both windows low to the floor and windows approximately fifteen feet higher.

The operable window area on the north façade is larger than the operable window area on the south façade. This was done to comply with an ASHRAE fundamentals [ASHRAE, 1997] recommendation that a greater leeward vent area promotes greater air velocities inside the occupied space, although the maximum airflow is gained when inlet and outlet areas are equal.

There are four banks of clearstory windows that automatically open when natural ventilation is in use. Occupants are notified of the availability of natural ventilation by lighted open window signs located in each quadrant of the building. Because of airflow obstructions created by mechanical rooms and restrooms, there are two natural ventilation assist fans at the east portion of the building. These fans are designed to pull air through the building and exhaust it on the north. The fan on the first floor is rated at 5,400 cfm. The fan on the second floor is rated at 2,800 cfm. With an approximate building volume of 480,000 ft^3, this represents an air change rate per hour of 1.025.

The building management system is based on software designed by Siemens. The original natural ventilation setpoints were based on recommendations found in Energy-10's simulation manual [SBIC, 1997]. Energy-10 is a commercially available building simulation program, designed to predict energy consumption for a variety of buildings. The conditions specified were 20-60% outdoor relative humidity with a temperature between 68-77°F. After a year of tweaking, these values were changed. As of December 2001, the building setpoints were as follows:

Condition	Strategy
Natural Ventilation	Between 46-72°F, natural ventilation is available. During this period, assist fans may or may not be turned on. It is up to the discretion of occupants to open windows.
Assist Fans	Interior temperature > 72°F, fans turned on. When temperature < 68 °F, fans turned off.
Summer Cooling	Between 77-78°F. Humidity is controlled to 50% with a 10% range.
Winter Cooling	Reach to 81°F before A/C or NV used. Drop to 78°F, system turned off. RH 65%, humidification off. Drop to 50% RH, humidification turned on.

Table 12 Summary of building operation setpoints and standards.

Shading of the south façade is provided by a large slotted wooden structure. The structure is designed to let direct sun penetrate during the winter, when the sun is low. During the summer, most direct solar gain is blocked. Interior aluminum Venetian blinds are available on the west, south, and east facades.

Insulation is provided in the form of structural insulated panels (SIP). The rating for the walls is R-23.5; the roof is rated at R-30. The SIPS consist of a layer of foam sandwiched in between two layers of wood. This design requires less wood than a conventional framing design.

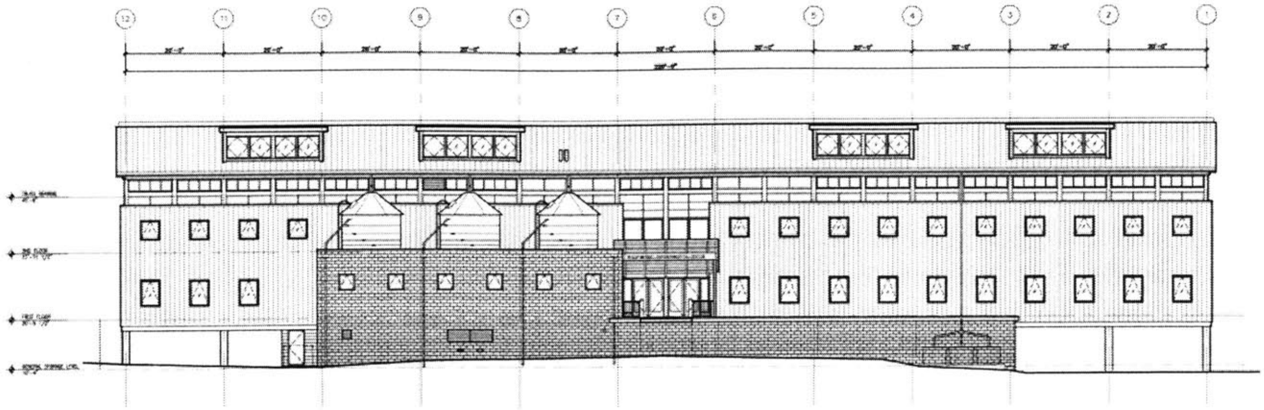


Figure 121 North elevation.

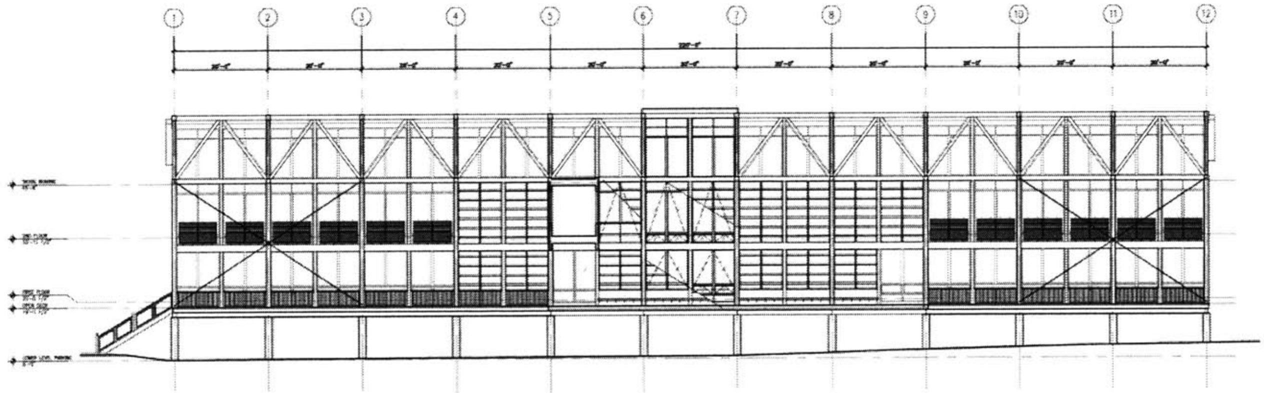


Figure 122 South elevation.

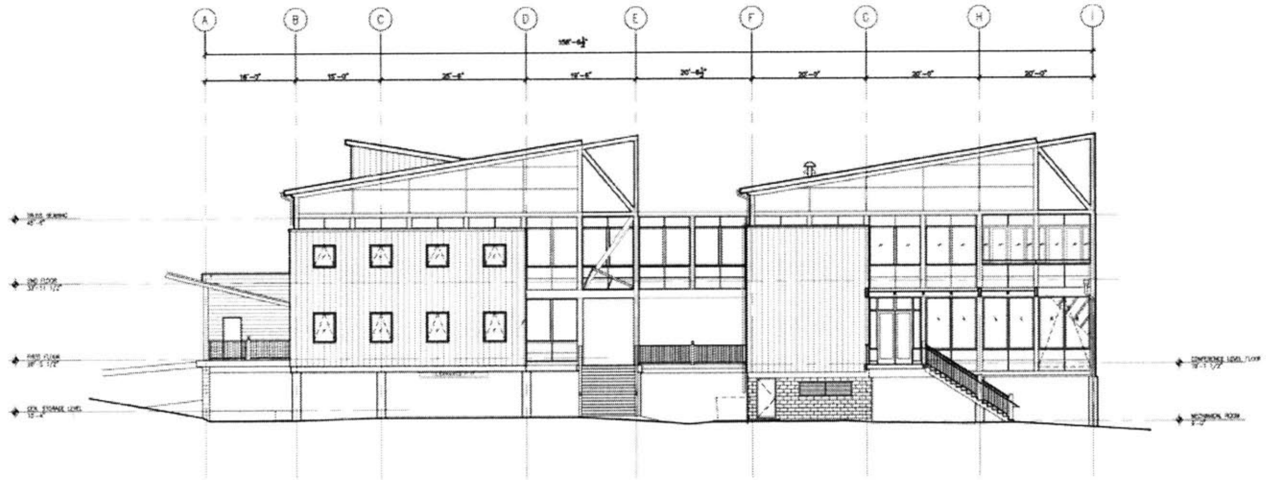


Figure 123 West elevation.

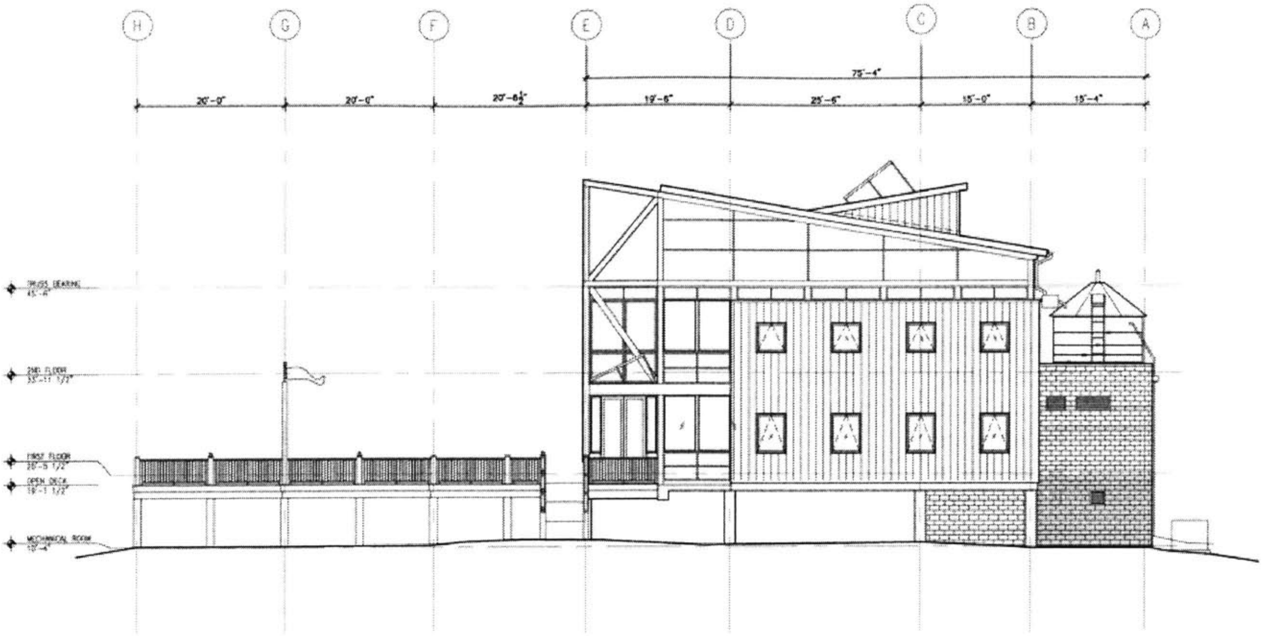


Figure 124 East elevation.

3.3.1 Lighting and Internal Loads

Lighting is controlled by an abundance of occupancy sensors. Each workstation has a motion sensor that shuts off the computer monitor and task lighting after a preset period of inactivity. Luminance sensors control hanging overhead lighting. For example, overhead lighting close to the south façade may operate at 25% on a sunny day, while the lighting closer to the north façade will operate at 75%, since there is less fenestration on the north. Each overhead lighting unit on the second floor features four 32-watt T-8 tube fluorescent bulbs. Two bulbs are directed upwards to provide indirect lighting, while the remaining two direct light downwards. There is currently no way to shut off just the top or bottom rows of lighting for additional energy savings. Additionally, there is no manual control of overhead lighting.

Additional loads come from occupants and computers. Almost every worker at CBF has a personal computer consisting of a CPU unit and a monitor. There are also laser printers and photocopiers scattered around the building. A summary of loads found on a typical day is given in the following table:

Location	Item	Quantity (Load)
1st floor west	Hanging light (tube)	13 x 4 (32-watt bulbs)
	Recessed lights (compact)	14 x 2 (18-watt bulbs)
	Square lighting fixtures (U)	12 x 2 (32-watt bulbs)
	Photocopier	1
	Laser Printer	1
	Workstation	33
	People	14
1st floor east	Hanging light (tube)	10 x 4 (32-watt bulbs); 3 x 2 (32-watt bulbs)
	Recessed lights (compact)	20 x 2 (18-watt bulbs)
	Square lighting fixtures (U)	6 x 2 (32-watt bulbs)
	Photocopier	1
	Laser Printer	1
	Workstation	27
	People	14
2nd west	Hanging light (tube)	23 x 12 (32-watt bulbs); 2 x 4 (32-watt bulbs)
	Workstations	36
	People	10
2nd east	Hanging light (tube)	20 x 12 (32-watt bulbs)
	Laser Printer	1
	Inkjet Printer	1
	Workstations	25
	People	13
2nd general	Laser Printer	3
	Photocopier	2
	Fax Machine	1
	Architectural Plotter	1
	Inkjet Printer	1
Atrium	People	2
	Workstations	2
	Laser Printer	2
	Photocopier	1
	Inkjet Printer	1
	Fax Machine	1

Table 13 Summary of lighting and internal loads.

3.4 Long-Term Instrumentation

3.4.1 Temperature

HOBO loggers were deployed in April of 2000 in various locations throughout the building. It was hoped that by placing sensors at window openings, the temperature of air leaving or entering the building could be determined. When it was found that airflow would often change directions, sensors were moved away from windows to locations with more stable temperature patterns. The final placement locations are as follows:

Location	Part Type	Logging Interval
First Floor West	HOBO® H8 Temp/External Logger w/ High Accuracy Temperature Sensor	10 minutes
Second Floor West		
Second Floor East (5 feet above floor level)		
Second Floor High (15 feet above floor level)		
Second Floor Atrium (5 feet above floor level)		
Second Floor Fan (at fan height)		
First Floor East (5 feet above floor level)	HOBO® H8 Logger for RH/Temp/2x External with Wide-Range Temperature Sensors	30 Minutes
Outside (6 feet above ground level)	HOBO® H8 Pro RH/Temperature Logger	10 Minutes

Table 14 Summary of instrumentation placement.

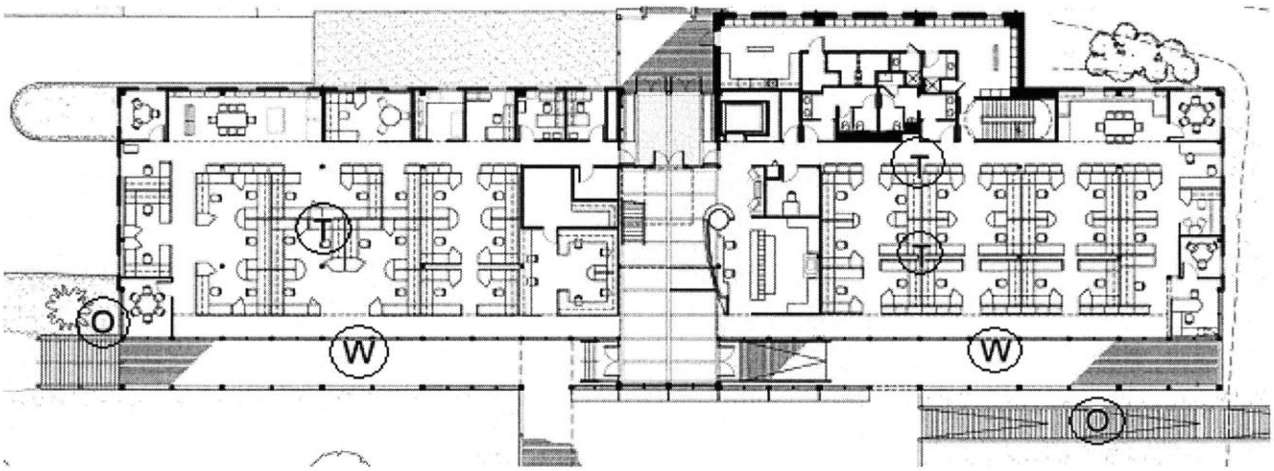


Figure 125 First floor sensor placement. KEY: C-wireless camera, T-temperature sensor, O-outdoor temperature sensor, W-window sensor. The outdoor sensor on the west side of the building was only in place temporarily to gauge variability in outdoor air temperature caused by uneven mixing of seaside air with landside air.

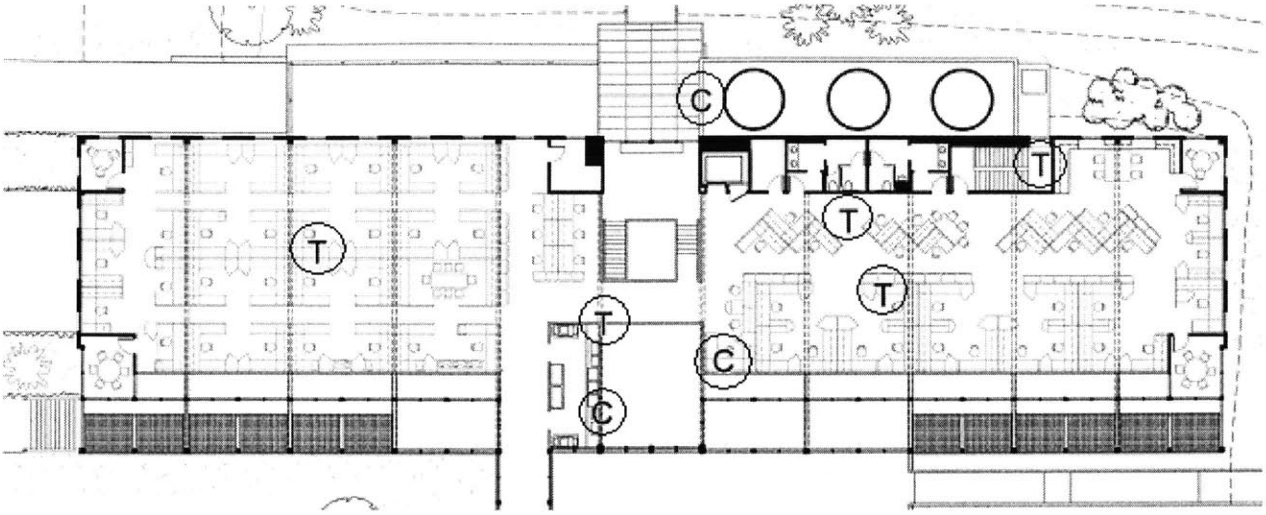


Figure 126 Second floor sensor placement. KEY: C-wireless camera, T-temperature sensor, O-outdoor temperature sensor, W-window sensor. The atrium is in the center of the building.

3.4.2 Weather Conditions

The Thomas Point lighthouse, located approximately two miles south of the building, was used for wind speed and wind direction data. The lighthouse is located on a buoy and is run by the National Oceanic and Atmospheric Association (NOAA). Wind data is recorded by the station every ten minutes. Historical data for the past twenty years is available online in ASCII text format [NBDC, 2002]. Originally, temperature data from the lighthouse was used for analysis, but it was found that the air temperature on water was sometimes drastically different from the air temperature on land, most likely due to the heat capacitance effect of large bodies of water [Allard, 1998]. The following plots represent summarized data taken at Baltimore-Washington International Airport [NOAA BWI, 2002].

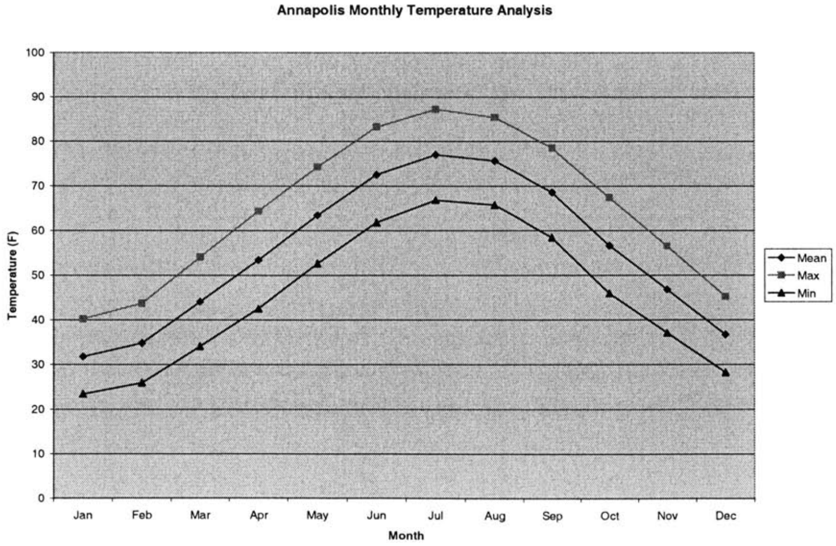


Figure 127 Annapolis average mean, average maximum, and average minimum monthly temperature.

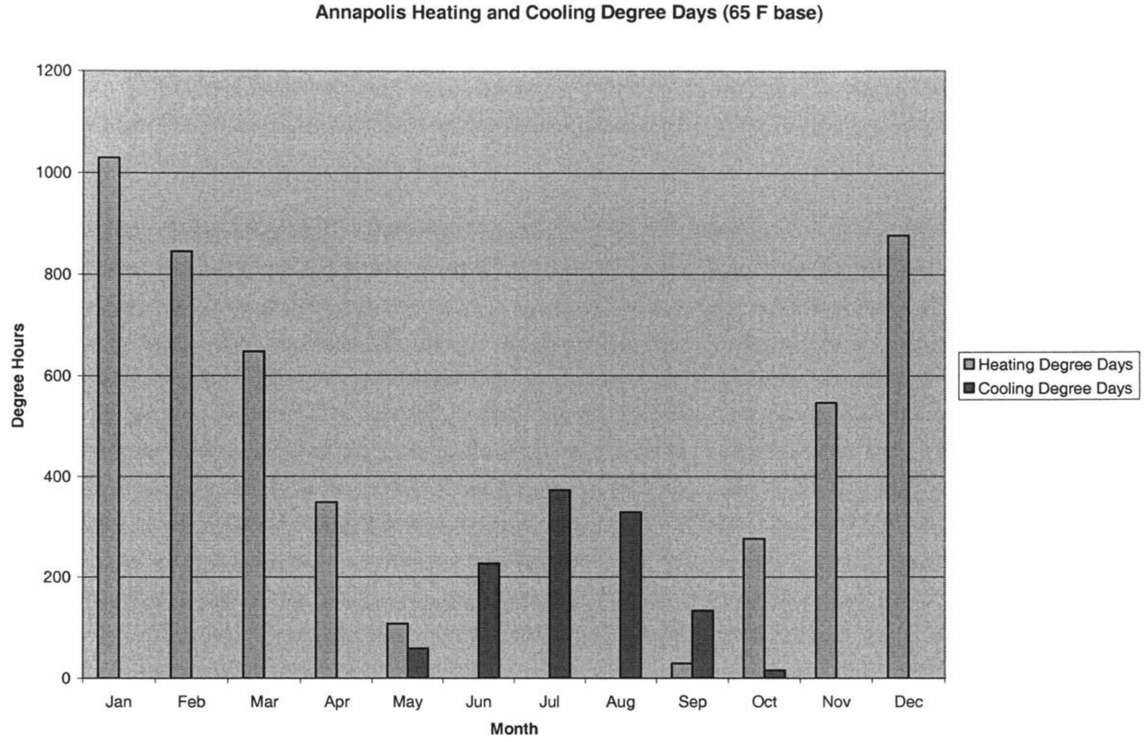


Figure 128 Annapolis heating and cooling degree hours.

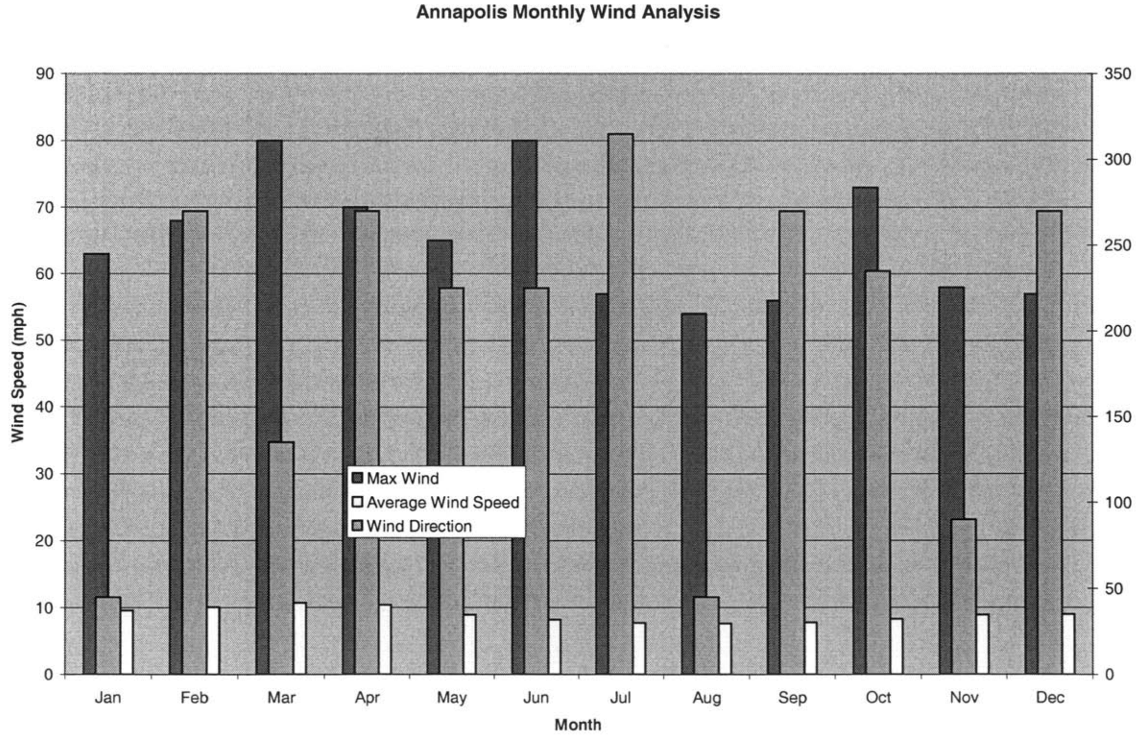


Figure 129 Annapolis average and maximum monthly wind speed and average wind direction.

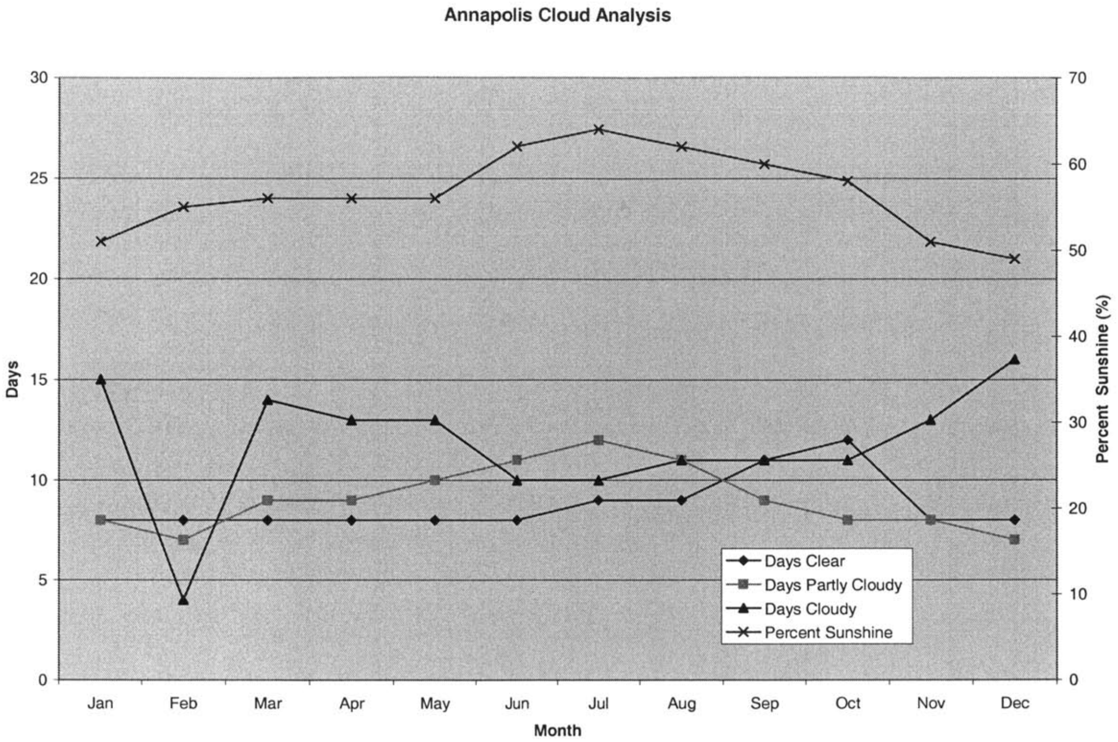


Figure 130 Annapolis monthly cloud and sunshine.

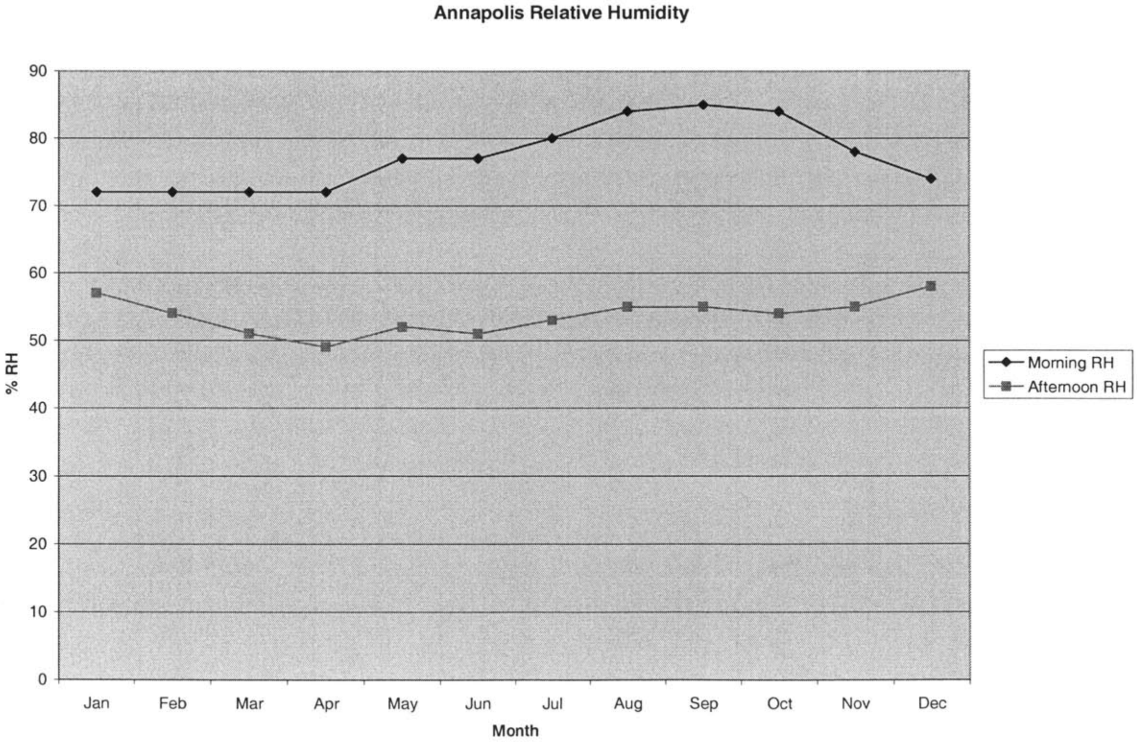


Figure 131 Annapolis average monthly morning and afternoon relative humidity.

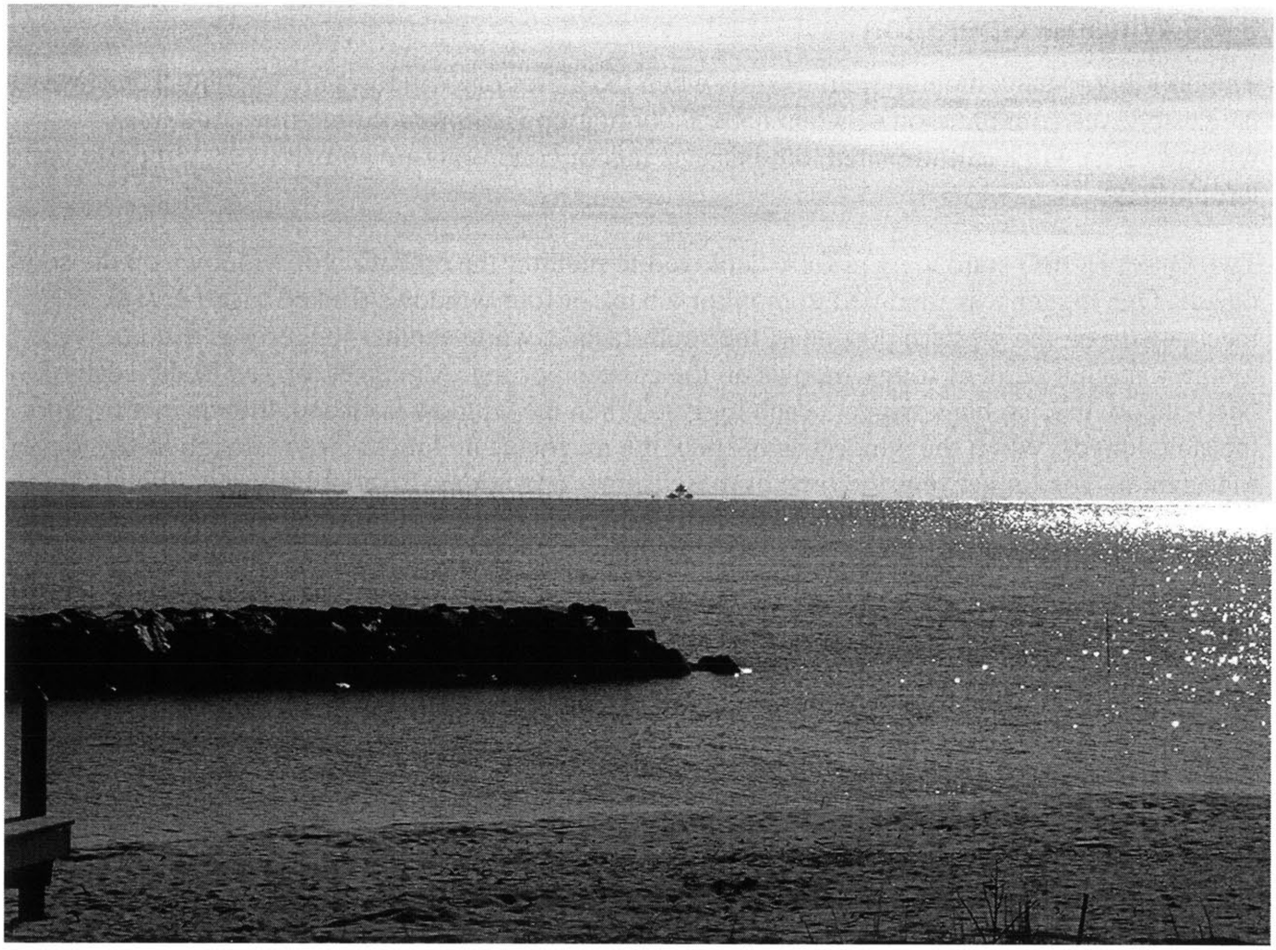


Figure 132 Thomas Point Lighthouse. This picture was taken fifty feet away from the building.

Station ID	TPLM2, National Buoy Data Center
Location	38.90°N, 76.44°W
Site Elevation	0.0 m above mean sea level
Air Temperature Height	17.4 m above site level
Anemometer Height	18.0 m above site level
Barometer Elevation	12.2 m above mean sea level

Table 15 Thomas Point Lighthouse specifications.

The ASHRAE 2% cooling design conditions for Baltimore-Washington International (BWI) Airport are 31°C db and 23°C mwb [ASHRAE, 1997]. BWI airport is located twenty-five miles northwest of the building site. Overall, the area experiences fairly hot and humid conditions during the summer, but the majority of the year, conditions are appropriate for natural ventilation. As seen in Figure 127, the July mean temperature is around 77°F, the cooling setpoint for the building.

3.4.3 Window Operation

The building management system records when the clerestory windows are opened. The BMS data also gives an indication of when natural ventilation is *allowed.* Sometimes, the open windows sign will be illuminated, but because indoor conditions are comfortable, windows are left closed.

Two Onset HOBO state loggers were deployed to monitor the operation of windows on the south façade. One logger was mounted to monitor a bank of four windows (linked together by one mechanism) on the western portion of the south façade, while another logger was used to monitor another bank of four windows on the eastern portion. A magnet affixed to the edge of one window in each bank triggers each logger. When the window is closed, the magnet triggers the state logger. When the window is opened, the magnet is no longer close enough to the logger to trigger it. The logger logs the time of these trigger operations. It should be noted that these loggers' data was compromised by work from building contractors on several occasions. At one point in experimentation, they were ripped off from their interior mounting locations to accommodate the installation of insect screens. They were subsequently mounted outside the building. In this case, salty sea spray prevented the operation of one of the loggers. They were then wrapped in foil tape and affixed to the building with Velcro. Later on, a contractor took one of the loggers off and remounted it upside down, preventing the magnet from making contact.

3.4.4 Video Monitoring

Being able to monitor all of the operable windows in the building proved to be a formidable task. The thought of asking some workers in the building to keep track of window operation was proposed, but eventually rejected as placing too much of a burden on the staff. Using pencil and paper sheets was also evaluated, but eventually thrown out as being too tedious. This contrasts significantly with the Broadmoor building, which had only one major operable window, making paper surveys feasible. Eventually, the use of a camera monitoring system was investigated and implemented. Several options were originally looked at: a four camcorder system with 4-channel splitter and time lapse VCR, wired PC web cams, or the use of a wireless camera system. The last option was chosen as being the least intrusive and least costly.

An investigation of available wireless systems revealed the dominating presence of X10's monitoring equipment, due in most part to very aggressive Internet marketing. The system chosen featured four wide-angle cameras, Multi-View software, a receiver and transmitter, two mini-tripods, and four motion sensors. The cameras rely on CMOS technology, in contrast to the significantly better CCD technology found in digital cameras and camcorders. This limited the quality of the captured images. The maximum resolution transmitted was 320 x 240 pixels. The cameras are water resistant, meaning they can withstand a splash of water, but cannot be submerged. The power packs are not water resistant and were thus sealed in zip-lock bags. The cost of the system was less than $400.

Each camera has a power pack with switches that allow each one to be set to a certain transmitter code. A controller, which is plugged into a wall outlet, sends signals to each camera through the building's wiring system. The controller receives signals from a transmitter hooked to the serial port of a Windows based PC. In this case, the system featured a Pentium III-350 MHz processor with 256 MB of RAM running Windows ME. A separate unit receives 2.4 GHz signals from each wireless camera. The receiver unit features an analog video-to-USB converter which plugs into a free USB port on the PC.

The effective range of the wireless unit proved to be a largely limiting factor. Although the manufacturer specifies a range of up to 200 feet, the actual range was approximately 100 feet, most likely because of the increased electrical interference found in a commercial building. The controller was also not able to consistently direct each camera properly; likely because a commercial building's electrical wiring system is zoned.

Cameras were eventually set in three locations. One camera was set to monitor windows on the north façade. Because of focusing limitations, the camera was only able to capture the operation of half of the windows on the western portion of the north façade. Another camera was set to monitor the eastern portion of the south façade. Due to poor contrast in some lighting conditions, it was sometimes hard to make out the position of windows with this camera. The third camera was also set to monitor the south façade, but often lost its signal, due to being the farthest from the base receiver. The Multi-View software was set to record an image from each camera every thirty minutes.

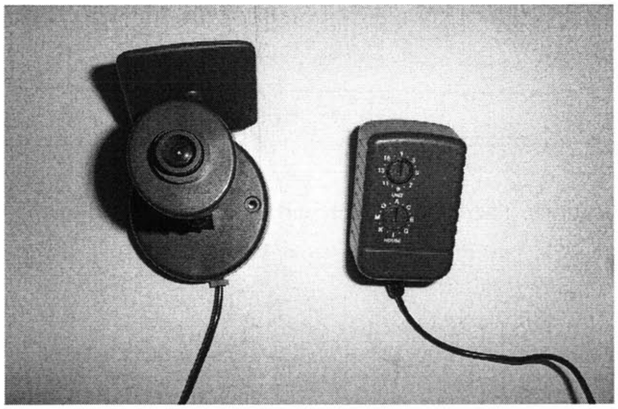


Figure 133 Wireless camera and its respective power pack. Each power pack has two adjustable dials to set each camera to a unique transponder code. The antenna on the camera itself is direction sensitive.

Figure 134 Video-to-USB converter and wireless receiver.

3.5 Short-Term Measurements

The same type of airflow and surface temperature measurements that were taken at Broadmoor, were also taken at the CBF building. Instrumentation specifications can be found in the Broadmoor instrumentation chapter. Airflow in the center of each zone of the building was measured using the Davis Instruments handheld anemometer. Airflow at open windows in each zone was also measured. Due to often shifting winds, it was difficult to attain repeatable velocity readings; the data collected is useful in showing the overall *magnitude* of flow. The Raytek thermometer was also used to measure surface temperatures in each zone. Measurements were taken at approximately half-hour to one-hour intervals.

3.6 Thermal Comfort Surveying

An important aspect of monitoring in the CBF building was the evaluation of personal thermal comfort. Originally, the building manager asked several workers to rate their thermal sensation on pre-made paper surveys in late May. After follow-up a month later, only one staff member had remembered to fill out surveys. After further discussion with CBF management, staff members were approached about participation more directly through email. Approximately 15 members then agreed to participate diligently. The locations of workers, each given a letter for identification, are provided in the following floor plans.

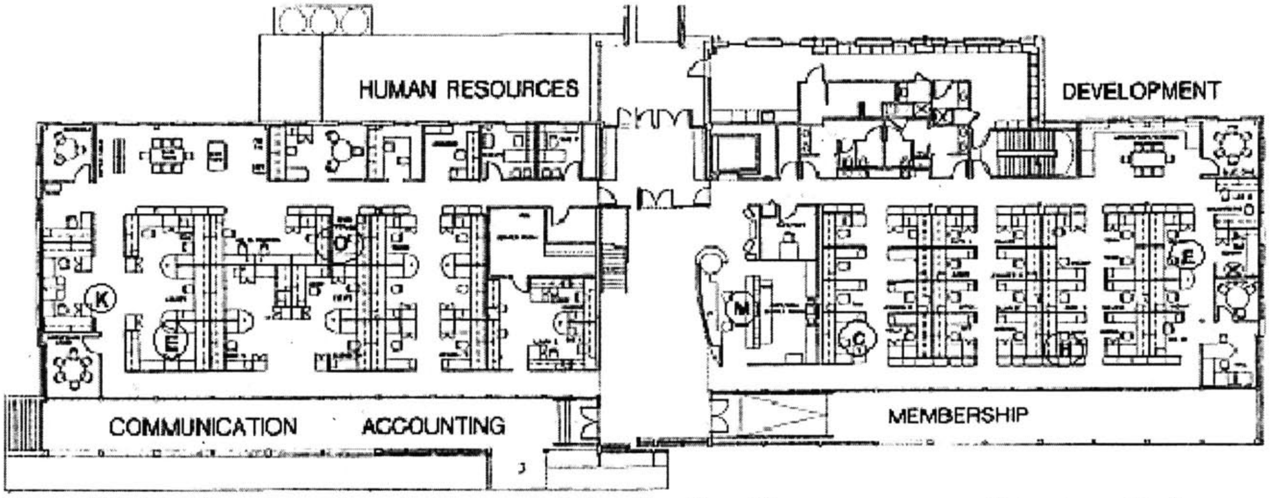


Figure 135 First floor thermal comfort survey participant locations. There were seven participants on this floor.

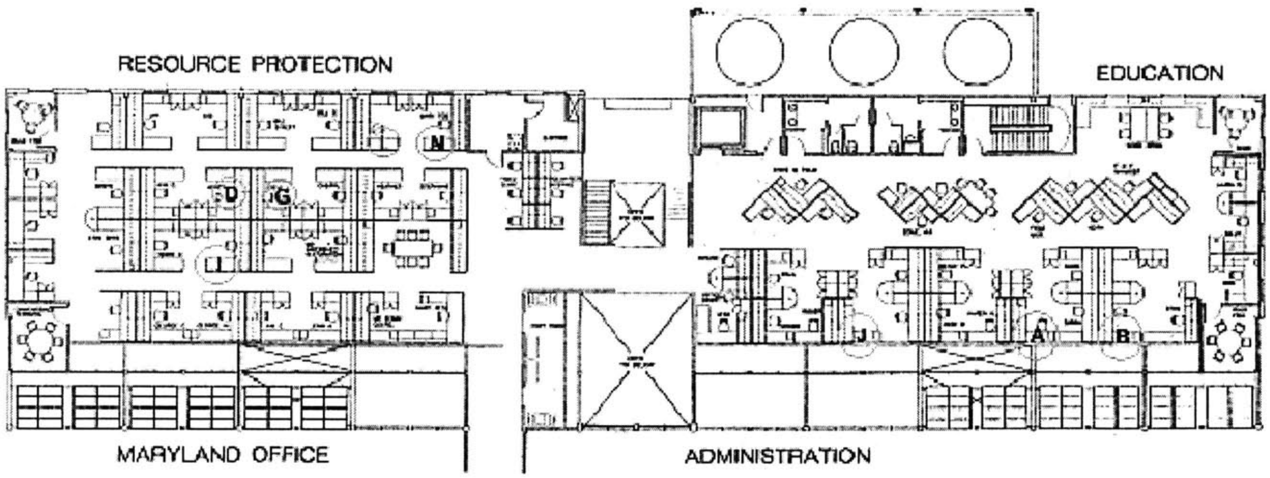


Figure 136 Second floor thermal comfort survey participant locations. There were eight participants on this floor.

Participants recorded their thermal sensation based on the ASHRAE seven-point scale twice a day, once at 10 am and then again at 3 pm. Participants were asked to record observations on any unusual odors, excessive noise, or other interesting environmental conditions. On a scale of 0-5, with a 5 indicating flying paper, participants recorded the relative magnitude of any air flowing through their work area. Finally, the status of the natural ventilation system and any significant window operation were recorded.

Each participant received a weekly email reminding him or her to fill out his or her survey sheets. This method of communication proved to be mostly effective. All fifteen participants filled out their surveys consistently. In late November, after a 10-week period of surveying, workers filled out a more detailed questionnaire. Results can be found in the Appendix.

3.7 Building Images

3.7.1 Exterior Images

Figure 137 North façade.

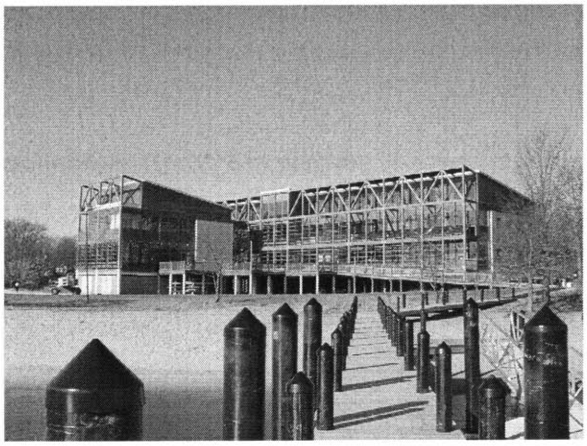


Figure 138 South façade. The building extension on the left is the conference center.

Figure 139 Another view of the north façade. Note the operable clerestory windows located on the roof. The main entrance is located at the center of the building.

Figure 140 Conference center. The building on the left features two floors of conference rooms. There is no provision for natural ventilation in that portion of the building. On the right, the fixed wooden shading system is visible, as well as a portion of windows on the south façade.

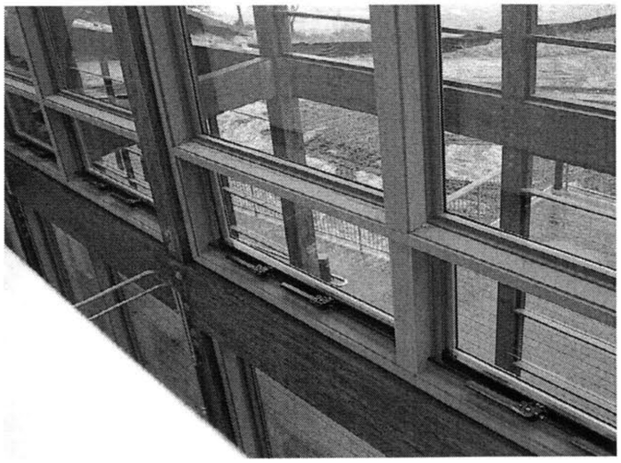


Figure 141 Bank of windows. These windows are located on the south façade. Crank and cable actuators open these top-hinged windows in groups of four.

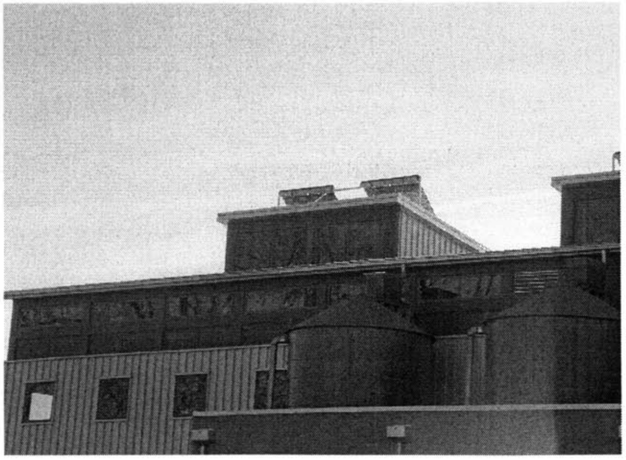


Figure 142 Clerestory windows. There are four sets of these windows. They are automatically opened when natural ventilation is available.

Figure 143 North façade. Some rainwater collecting cisterns are visible in this photo. All windows are operable using individual hand cranks. The space underneath the building houses approximately fifty parking spaces.

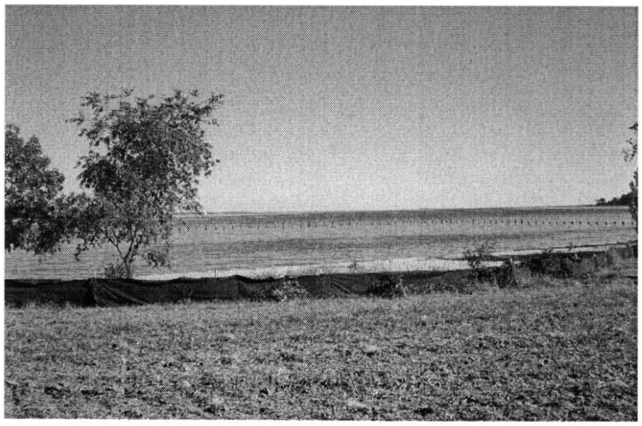


Figure 144 Beach. The building is located one hundred feet from the water.

Figure 145 Parking lot. The lot is not paved to allow runoff to sink into the ground and run into specially designed collection areas.

Figure 146 Solar shading device. This device allows low sun to penetrate during the winter, while blocking high sun during the summer.

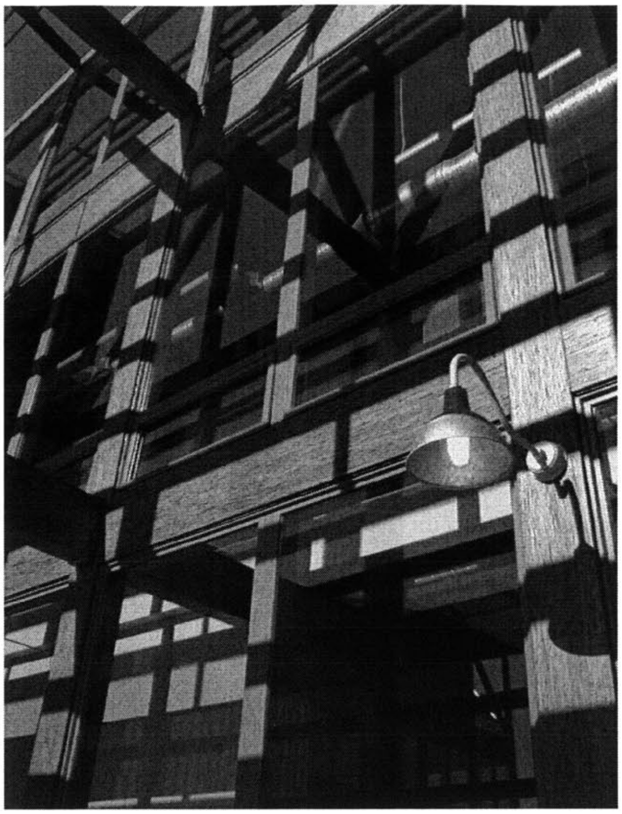


Figure 147 South façade. In this photo, bands of shadows caused by the solar shading device are clearly visible.

Figure 148 Upper south façade window. In these two window pictures, the crank mechanism was not yet connected.

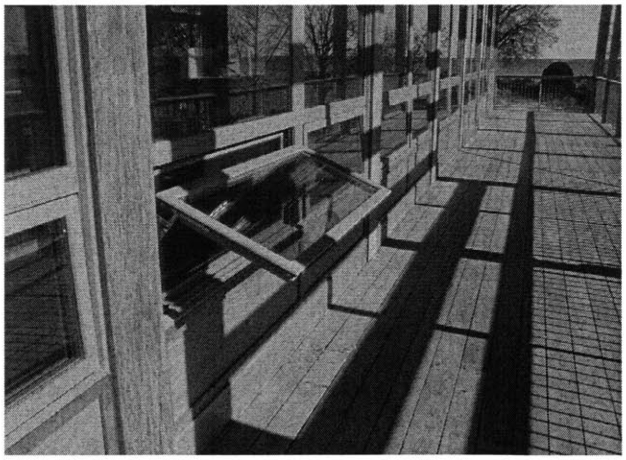


Figure 149 South façade window. This is the maximum extent that windows on the south can open.

3.7.2 Interior Images

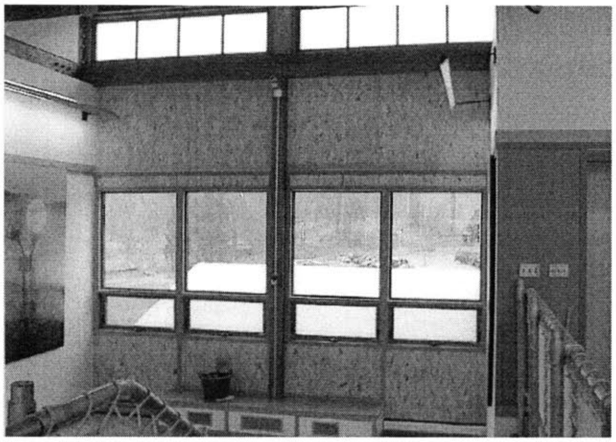


Figure 150 Atrium. The windows at the bottom are operable using individual hand cranks. The windows up high are solely for natural daylighting and do not open.

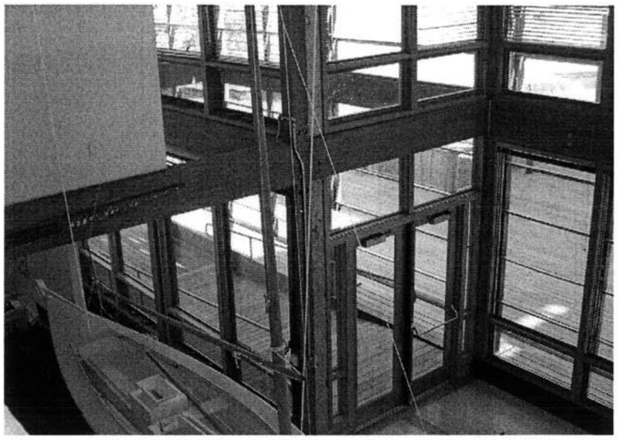


Figure 151 Atrium. The atrium receives very little direct airflow when natural ventilation is used. The closest operable windows are located in the bottom left of the photo.

Figure 152 View of south façade from first floor east office area. Portions of the ceiling were left open for cost savings.

Figure 153 First floor east office area. The large vent on the rear wall feeds to the larger of two natural ventilation assist fans.

Figure 154 Second floor. All cubicles are fairly low to allow air to pass freely. The solar shading device is clearly visible on the right. The shading device is broken up into two components. For the top bank of windows, a horizontal slatted overhang provides shading, while a vertical wall of wooden slats shades the rest of the windows. Hanging lights adjust to the amount of available ambient light. Sometimes the hanging lights will move when airflow through the building is significant.

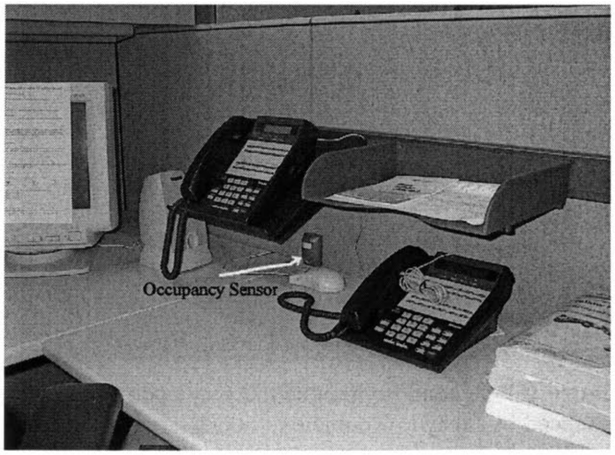


Figure 155 Workstation occupancy sensor. Each workstation features a sensor which automatically shuts off the computer monitor and task lighting when movement is not detected for fifteen minutes.

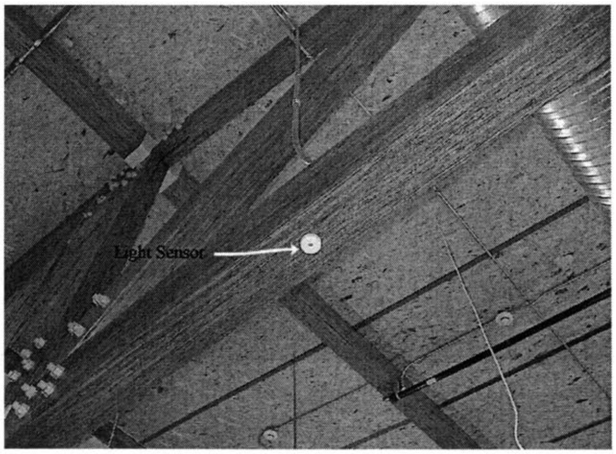


Figure 156 Lighting sensor. Sensors such as this are located throughout the building to control the intensity of fluorescent lighting. White noise generators are also hung from the ceiling.

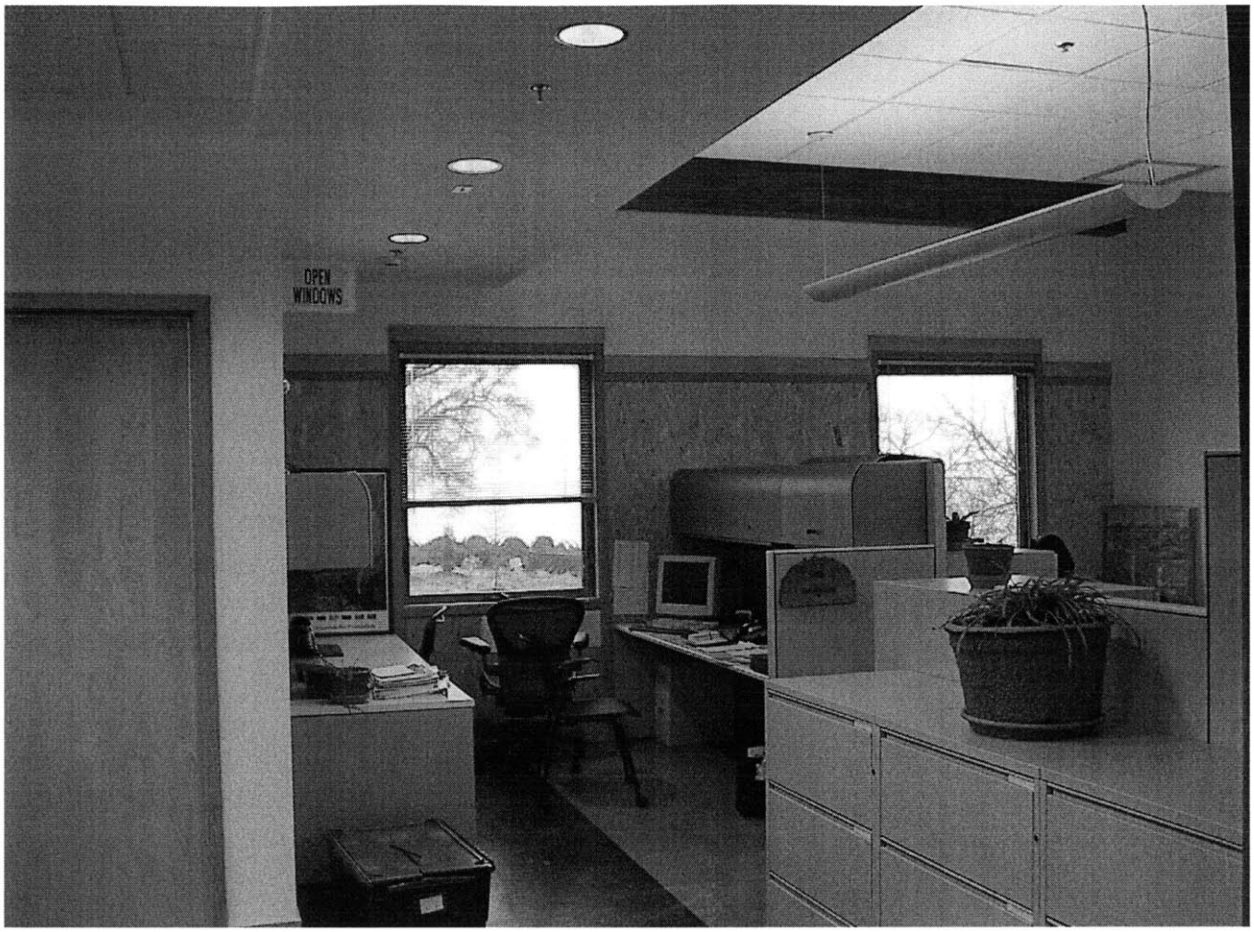


Figure 157 Open windows sign. The sign illuminates when natural ventilation is available. There is one sign for each quadrant of the building. The two windows visible face east.

Figure 158 Second floor. Each row of hanging lights can be dimmed in 25% increments. Typically, the row of lights closest to the north-facing back wall, in this picture, is kept on.

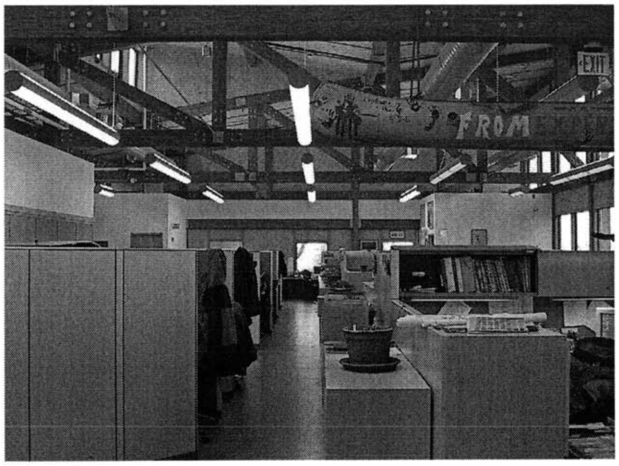


Figure 159 Second floor. Note the very open floor plan enhanced by fairly low cubicle dividers.

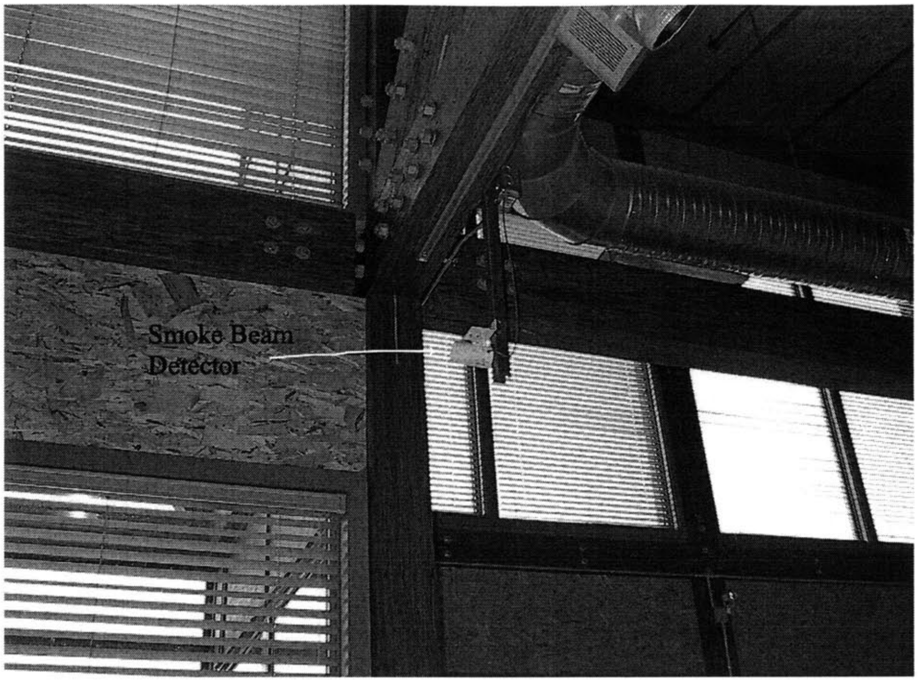


Figure 160 Smoke beam detector. Several detectors are located throughout the building to detect smoke traveling from the first floor to the second floor. This was one of the primary ways fire codes were satisfied with such an open plan building.

Figure 161 First floor corridor. The rows of windows low to the ground are operable. The open channel allows warm air to rise from the first floor up to the second floor for venting through the clerestory windows. Note the aluminum blinds. They are all operated with cords that reach down to the first floor.

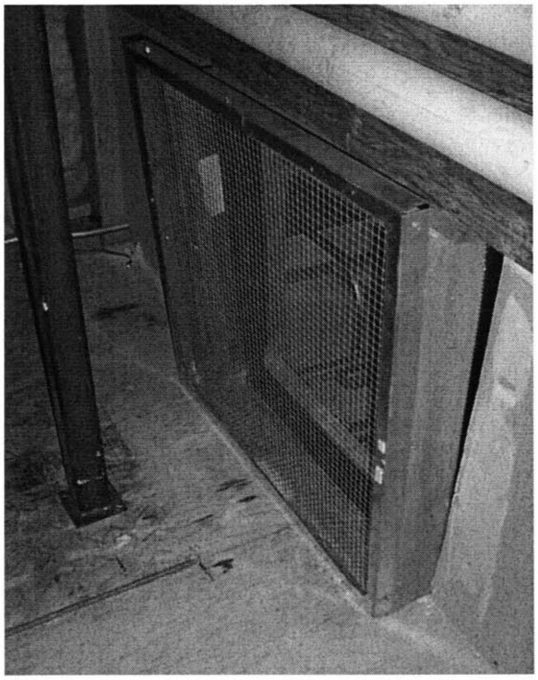
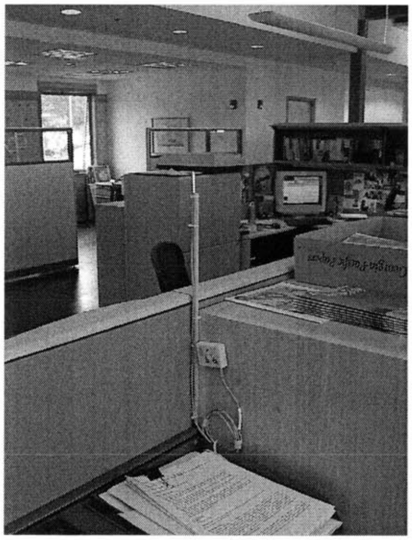


Figure 162 Air vent. This vent is located in the mechanical room on the second floor. When the natural ventilation fan in the mechanical room is operating, air is brought from the occupied spaces through this vent.

3.7.3 Instrumentation Images

Figure 163 Wireless camera. The camera sits unobtrusively on a ledge to view the status of windows on the south façade.



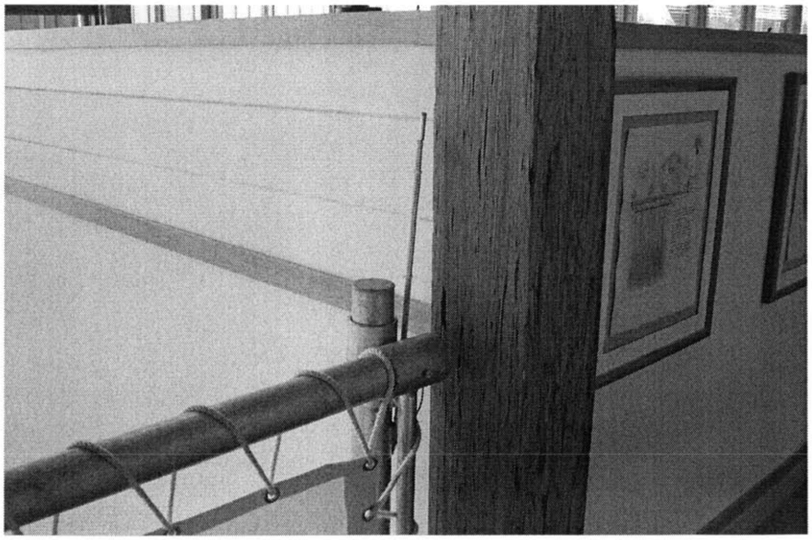


Figure 164 First floor west temperature sensor.

Figure 165 Atrium temperature sensor. All temperature sensor probes were mounted on a wooden dowel to enhance visibility. The sensors were coated with a thin layer of reflective aluminum paint to reduce the effect of solar radiation.

Figure 166 First floor east sensor.

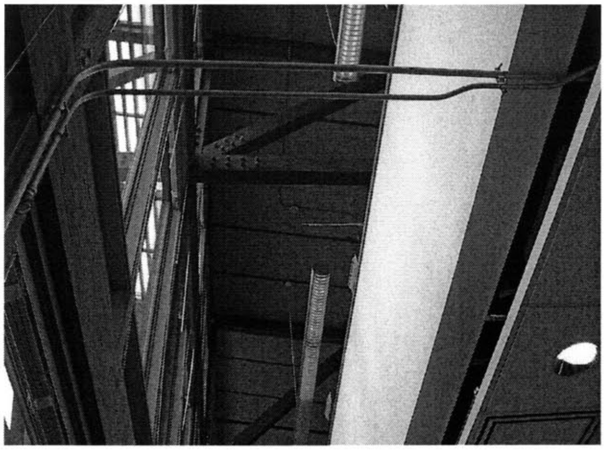


Figure 167 Ledge temperature sensor. This sensor was placed to evaluate the temperature of air rising from the first floor to the second floor. Due to significant direct sun, this sensor was eventually moved.

Figure 168 Outdoor temperature sensor. This sensor was mounted underneath an access ramp leading from the building to the beach. To the left of the sensor is the parking area. The sensor was shielded with reflective aluminum foil tape.

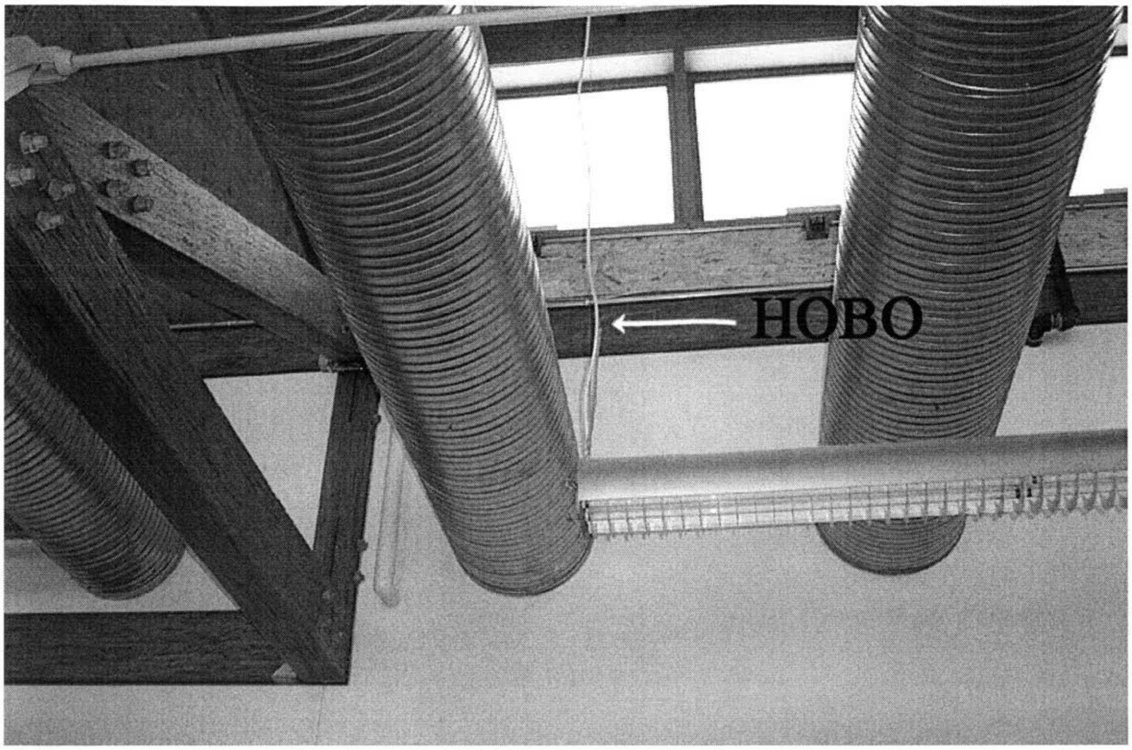


Figure 169 Clerestory temperature sensor. This sensor was mounted as close to a clerestory window as possible. It is located approximately halfway up the light's supporting wire. The upper lights directly underneath the sensor were shielded to minimize any thermal plumes.

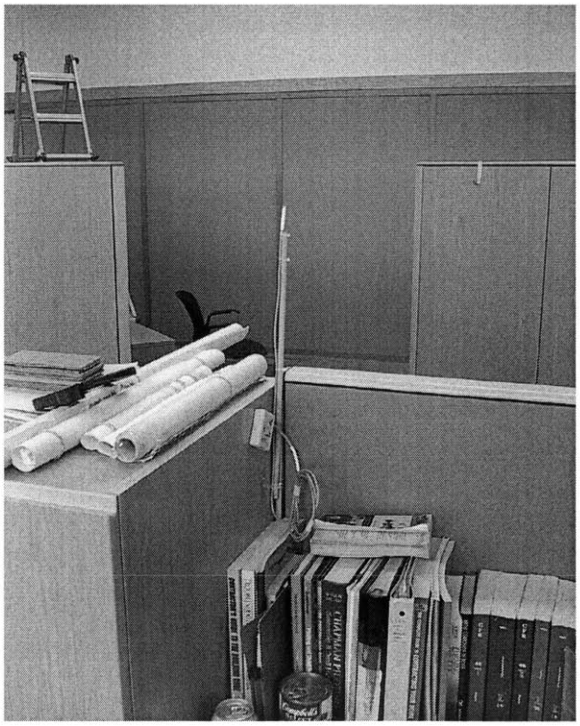


Figure 170 Second floor east temperature sensor.

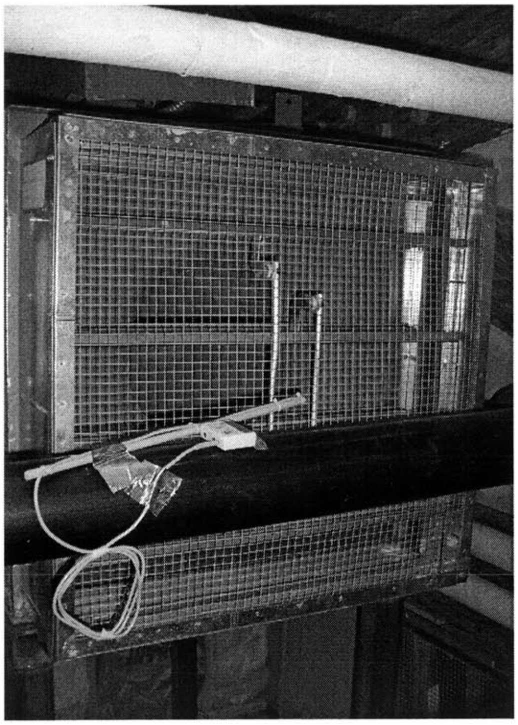


Figure 171 Fan temperature sensor. A temperature sensor was placed slightly inside the second floor's natural ventilation fan housing.

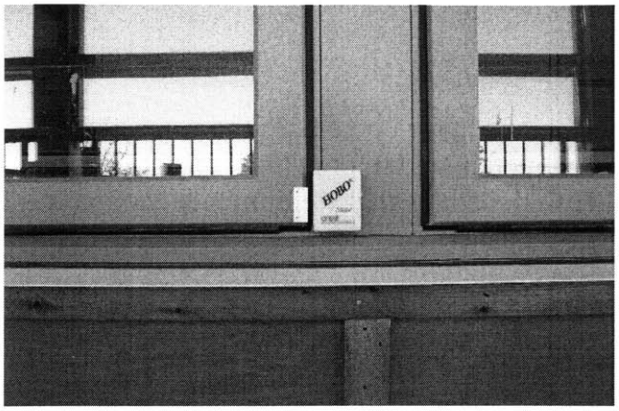


Figure 172 Window state logger. The white sensor on the window itself is a magnet. When the window is open, it is no longer close enough to the logger to activate it.

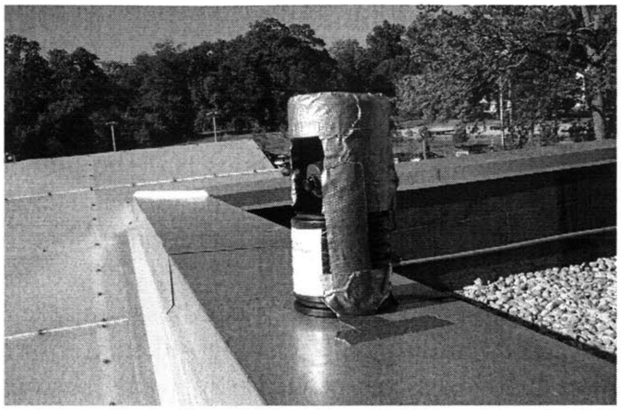


Figure 173 Outdoor wireless camera. Custom-made housings for cameras mounted outdoors were made out of PVC drainage pipe. The top of the pipe was covered with duct tape to keep rain off the camera.

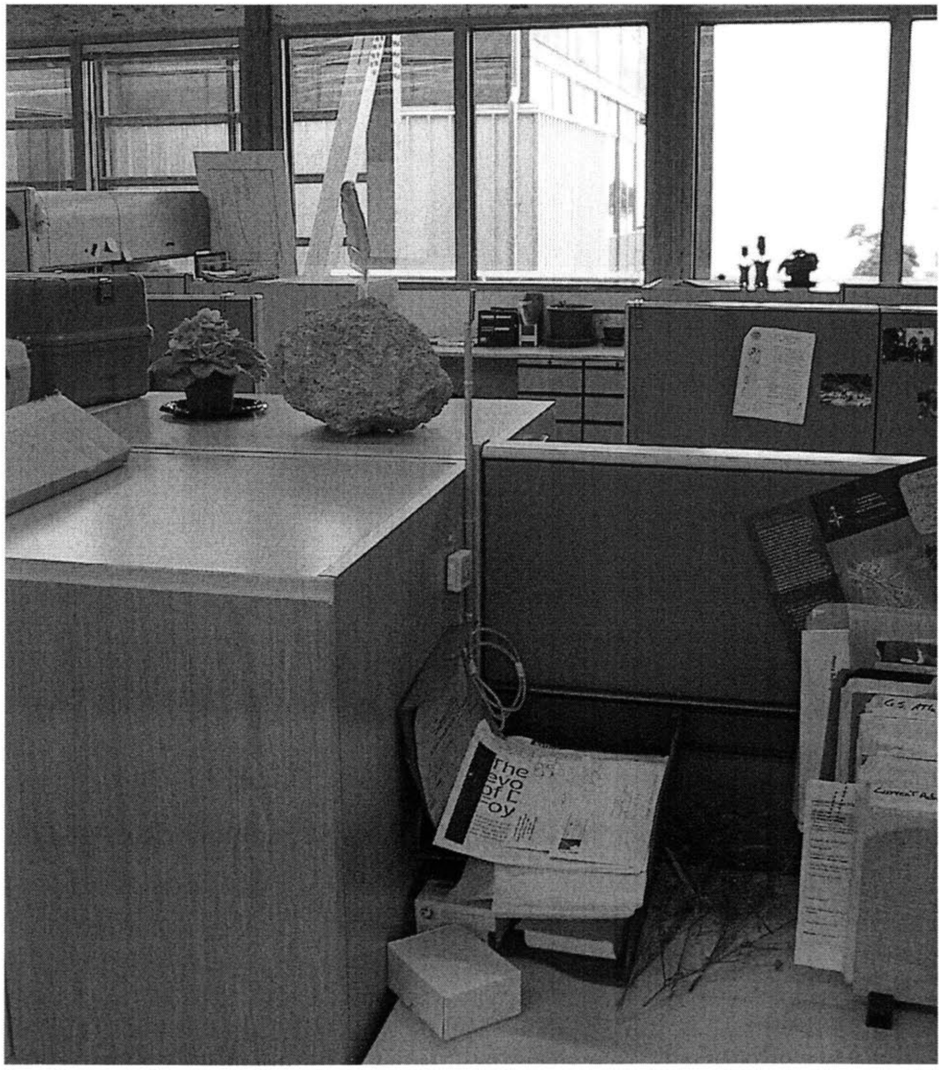


Figure 174 Second floor west temperature sensor.

Chapter 4 Simmons Hall

4.1 Description

Simmons Hall is a new MIT undergraduate dormitory planned for opening in the August of 2002. Upon looking at Simmons Hall, both under construction and in drawings, one notices a very unique form. Underlying the form are several design features that were intended to make the building energy-efficient and comfortable for its occupants. The building is 100 feet high with ten floors. The expected capacity of the dorm is set at 350 persons. Steven Holl, the principal architect on the project, based his ideas on the concept of porosity. The result of this theme is a building with a sponge-like exterior coupled with interior rooms of greatly varying shapes and sizes connected vertically by abstracted shaped atriums. Services engineering was done by Arup.

Natural ventilation was considered in the design of the dorm. Originally, cross ventilation, single-sided ventilation, stack ventilation, natural daylighting, and night cooling were specified as ways to cool the building and achieve optimal occupant comfort. What was desired on paper became difficult to implement in reality.

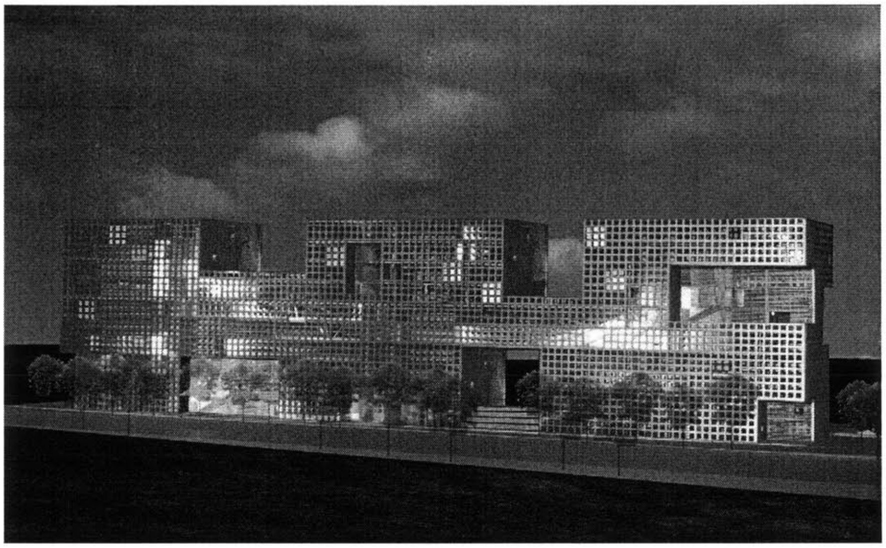


Figure 175 Exterior model view.

4.2 Ventilation Strategies

4.2.1 Cross Ventilation

Cross ventilation was initially specified as the dominant natural ventilation cooling method. To achieve this, a narrow building footprint was specified. A width of 40′, coupled with a south-facing orientation directed at predominant winds, were design features included to achieve a desired air change of up to 30 per hour. The barrier to this strategy was fire regulations from the state of Massachusetts. Rooms in Simmons Hall are laid out in a double-loaded corridor configuration. Problems arose with how to maintain each room as its own zone, with the requirement that corridor-adjacent walls be fire-rated. It was initially proposed that vents in those walls be installed. Fire dampers would close the vents when a fire alarm went off. This strategy was abandoned due to complication with how to reset each damper after even false alarms. The cost for electronically controlled dampers, as opposed to mechanically actuated dampers, proved to be cost prohibitive and too complicated. In general, there was a reluctance to work with fire code regulators to use cross ventilation.

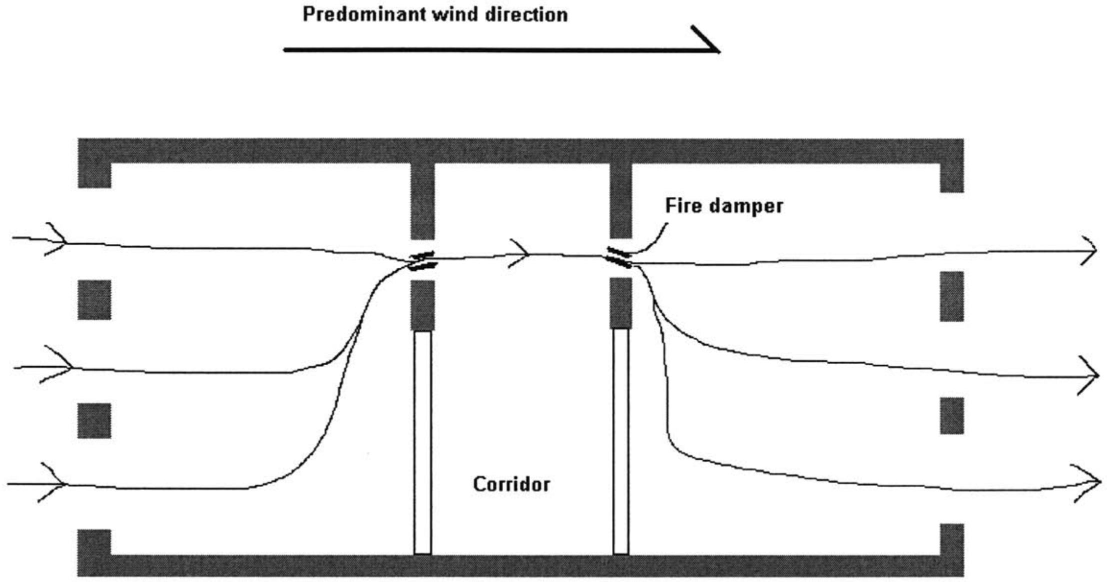


Figure 176 Diagram of cross ventilation strategy.

4.2.2 Single-sided Ventilation

When winds are not sufficient for cross ventilation, single-sided ventilation is possible. In each room, there are three rows of 2 x 2 feet operable windows. It is expected that the bottom and top rows of windows be opened. Cool air enters the room through the bottom windows, is heated up by internal loads, and then exits through the top windows. In computational fluid dynamic simulations, this strategy produced up to 15 air changes an hour under the most ideal conditions [Allocca, 2001]. Cross ventilation is still the optimal strategy though, because it can potentially yield 30 or more air changes an hour.

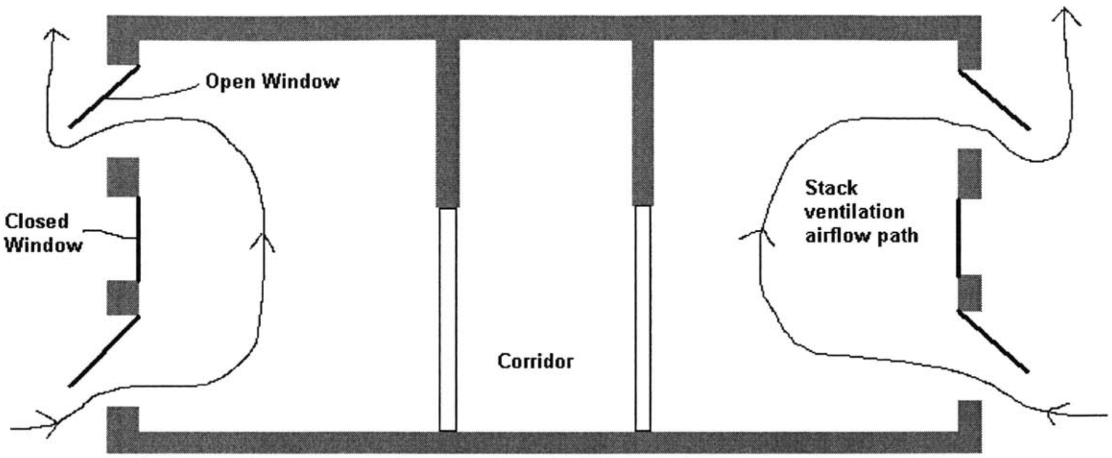


Figure 177 Diagram of single-sided ventilation strategy

Figure 178 Interior view of windows in a double room.

4.2.3 Stack Ventilation

There are several multi-story atrium spaces in the building. It was originally envisioned that these atriums would serve as "lungs" for the building, bringing in air and light. They were also envisioned for stack ventilation usage. Due to fire regulations, it was difficult to incorporate atriums with the size originally desired. In the final building, atriums that are two to three floors in height are included. The tops of the atriums are strictly sealed off to prevent any major stack effect from moving smoke in one portion of the building to another during a fire.

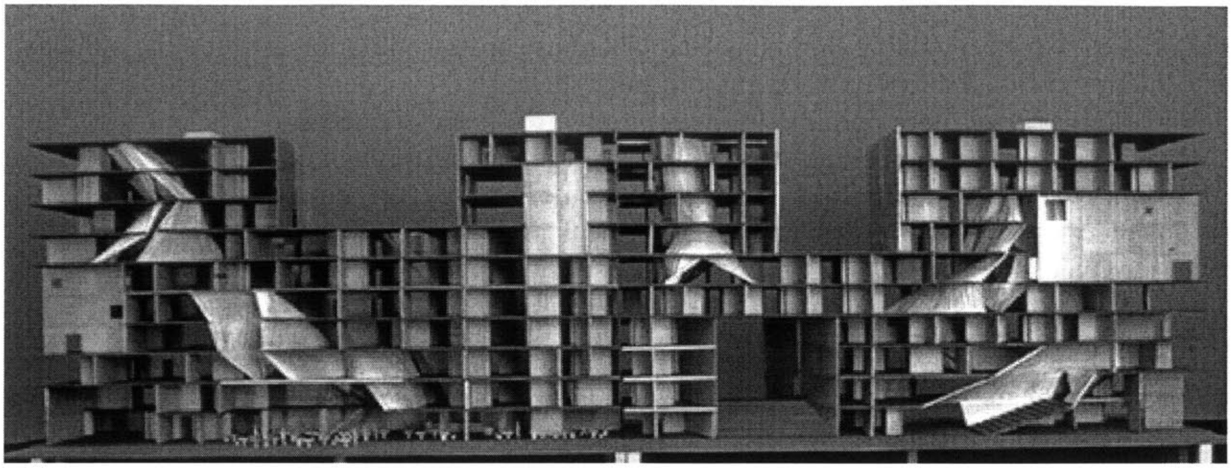


Figure 179 Model of interior building layout, including preliminary locations of atriums.

4.2.4 Night Cooling

Simmons Hall does not feature a steel space frame, like most typical buildings. Instead, prefabricated concrete panels were used. The reason behind using pre-made panels was to have concrete walls of high enough quality to not have to add wallboard or other furnishings that would minimize the availability of thermal mass. The exterior wall includes almost 18 inches of concrete with another three inches of hard foam insulation. During the day, it is hoped that the high amount of thermal mass will temper any significant exterior temperature swings. At night, cooler air is brought in to flush the thermal mass. The only problem with this concept is that a dormitory's load schedule varies drastically from a commercial building's schedule. Peak loads occur in the evening in a dorm; night cooling would be less effective.

Figure 180 Exterior view of unfinished façade.

4.2.5 Alternate Cross Ventilation Strategy

It was originally conceived that Simmons Hall would use cross-ventilation as a cooling strategy. Due to fire regulations, direct transfer of air through the central corridor from one side of the building to the other was not permitted. It was proposed to install a duct above the corridor, with the idea that cross ventilation could still function by bringing air through this duct. It was later proposed that the entire plenum space above the corridor be used, meaning that there is no additional ductwork for cross ventilation. Basic calculations predicting the net flow through this plenum have been performed.

4.3 Cross Ventilation Modeling

The following is a description of how cross ventilation pressure losses through an open plenum were calculated. The first part focuses on loss through straight ducts and the open plenum. The remaining losses are calculated using loss coefficients from a standard handbook. The following equations are referenced from Frank White's Fluid Mechanics text (1994).

For incompressible flow in ducts, the lost head can be expressed as

$$l_f = f \frac{L}{D} \frac{\overline{V}^2}{2g}$$

where:

f = Moody friction factor
L = length of plenum
D = diameter of plenum
V = average velocity in plenum
G = gravitational acceleration

For a non-circular duct, the hydraulic diameter should be used:

$$D_h = \frac{4A}{P}$$

where:

A = cross-sectional area
P = wetted perimeter

The lost pressure is given by:

$$\Delta p = \rho g l_f$$

where:

ρ = density of air

Before we can calculate l_f, we must calculate the Moody friction factor. This given by:

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left[\frac{e}{3.7D} + \frac{2.51}{\mathrm{Re}_D \sqrt{f}}\right]$$

where:

e = absolute roughness (*e* = 3 mm for rough concrete)
Re_D = Reynolds Number

The Reynolds Number is:

$$\mathrm{Re}_D = \frac{u_{av} D_h}{\upsilon}$$

where:

$\upsilon = \mu/\rho$

In calculations, the principal driving force to consider is wind. The net pressure on the building due to wind can be calculated with:

$$\Delta p_{wind} = \frac{1}{2} C_p \rho v^2$$

where:

C_p = coefficient of static pressure
v = time-mean wind speed at opening level

The static pressure coefficient varies from building to building. The undergraduate dormitory is considered a low-rise building because its height is less than three times its crosswind width. Using a chart from the ASHRAE fundamentals handbook [ASHRAE, 1997, we can select an approximate C_p value. We use one C_p value of 0.6 for the windward side of the building (positive pressure) and one of –0.3 for the leeward side of the building (negative pressure, *vacuum*). We neglect the sides of the building.

For turbulent flow through large openings, the flow rate is given by:

$$Q = C_d A \sqrt{2 \Delta p}$$

where:

C_d = discharge coefficient, which is dependent on the sharpness of the opening and the Reynolds number. For a sharp opening, we use C_d = 0.6.

4.3.1 Calculation Using Loss Coefficients

The handbook of hydraulic resistance by Idelchik (1996) was used to determine relevant coefficients to use in calculating the pressure drop in the overall system. The following table indicates the coefficients used:

Resistance Location	**Coefficient** ($\zeta = \frac{\Delta p}{\frac{1}{2}\rho v^2}$)
Window (all open to 60 degree angle, 0.1 m^2 effective area for each)	0.1
Entrance to duct (3 x 3 ft, open grate)	0.1
Turning vanes (straighten flow, perpendicular to flow)	0.14
Expansion from duct (3 feet wide x 8 inches high) to plenum (7 feet wide x 10 inches high)	0.8 (0.20 for tapered)
Obstruction (cable tray, pipes, etc. x 10)	0.03 each
Contraction from plenum to duct	0.45 (0.20 for tapered)
Discharge from duct to room (3 x 3 ft, open grate)	0.1
Plenum Resistance	0.62 Pa for 0.7 m^3/s flow
Total Pressure Drop	**2.11 Pa**
Available Pressure at 5 mph	**2.7 Pa**

Table 16 Table of resistance coefficients.

The velocity value, used in calculations, corresponds to the particular cross-sectional area of the flow resistance item in question. For example, for the entrance and exit, the velocity corresponding to the 3 x 3 foot opening area, with a flow rate of 0.7 m^3/s, is used. For the contraction and expansion coefficients, the velocity *downstream* of the flow change is used.

It was assumed that obstructions in the plenum, other than mandatory pipes and cable trays, would be kept to a minimum. It was also assumed that both rooms would be well sealed, with a well-mixed, uniform temperature distribution. The plenum wall material was assumed to be smooth concrete with a roughness of 0.15 mm.

4.3.2 Calculation of Resultant Room Temperature

We use a sol-air temperature to combine convective, conduction, and radiation wall heat transfer through the roof of Simmons Hall [ASHRAE, 1997].

$$t_e = t_o + \alpha I_t/h_o - \varepsilon \Delta R/h_o$$

where:

t_e = sol-air temperature
t_o = dry bulb temperature outdoors
α = absorptance of surface for solar radiation
α/h_o = surface color factor = 0.025 for light colors and 0.052 for dark colors
I_t = total incident solar load
$\varepsilon \Delta R/h_o$ = long-wave radiation factor = -3.9 °C for horizontal surfaces

We assume a peak solar radiation value of 940 W/m^2 for July. We also assume an outdoor temperature of 31°C. The area of radiation is approximately 30 m^2 on a light colored surface. The heat gain is calculated with [Incropera & DeWitt, 1996]:

$$Q_{air} = UA(t_e - t_i) + Q_{internal}$$

where:

U = wall transmission coefficient (W/m^2C)
A = wall heat transfer area (m^2)
t_i = desired indoor temperature (°C)
$Q_{internal}$ = internal heat loads (W)

The resultant space temperature, without incorporation of thermal mass is:

$$T_{air}(t) = \frac{Q_{air} + Q_{vent}\rho_{air}c_p T_{out}}{Q_{vent}\rho_{air}c_p}$$

where:

Q_{air} = net internal/fenestration loads, W
c_p = heat capacity of air, J/kg K
Q_{vent} = flow rate of outside air into space, m^3/s
T_{out} =outdoor air temperature, K

We assume a three-inch layer of insulation consisting of hard foam board (k = .027 W/m·K).

Air change rate per hour	Resultant room temperature
1	37.0°C
5	32.2
10	31.6
30	31.2

Table 17 Resultant room temperature for various air change rate.

Proper ventilation is crucial to maintaining acceptable interior temperatures. With an outdoor temperature of 31°C, the interior temperature rises to 37°C when one air change per hour is available. When the air change rate is increased to five per hour, the interior temperature drops by almost 5°C. With thermal mass effects, we can expect the interior temperature to be even lower.

4.4 Discussion

The resistances at the entrance and exit to the plenum could prevent cross ventilation from occurring. The plenum openings must be designed to minimize losses. One way to accomplish this is through the use of curved bell-mouth openings and transitions. In general, sharp edges should be eliminated. To keep flow going straight, turning vanes should be incorporated after the entrance to the duct as shown in the following diagram.

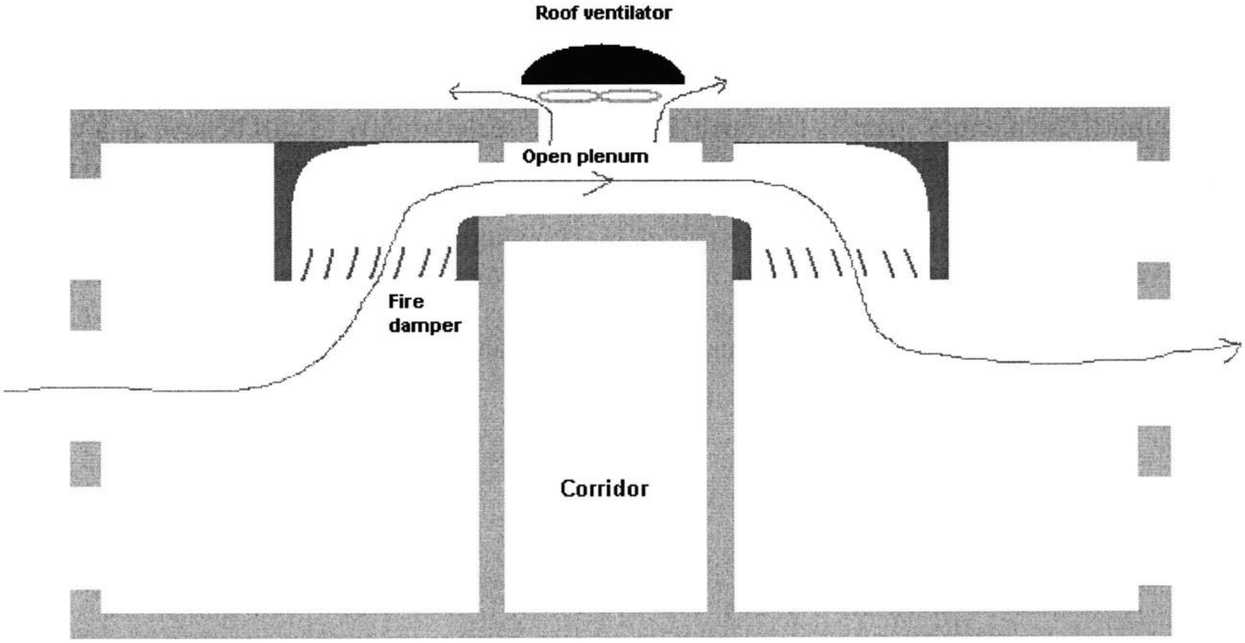


Figure 181 Recommended open plenum cross ventilation layout. See Figure 182 for the overhead view of the system.

To further minimize losses, it is recommended that ductwork be installed above the bathroom, so that the transition from a 3 foot wide opening to a 7 foot wide plenum space is much more gradual. The alternate path can be seen in Figure 182.

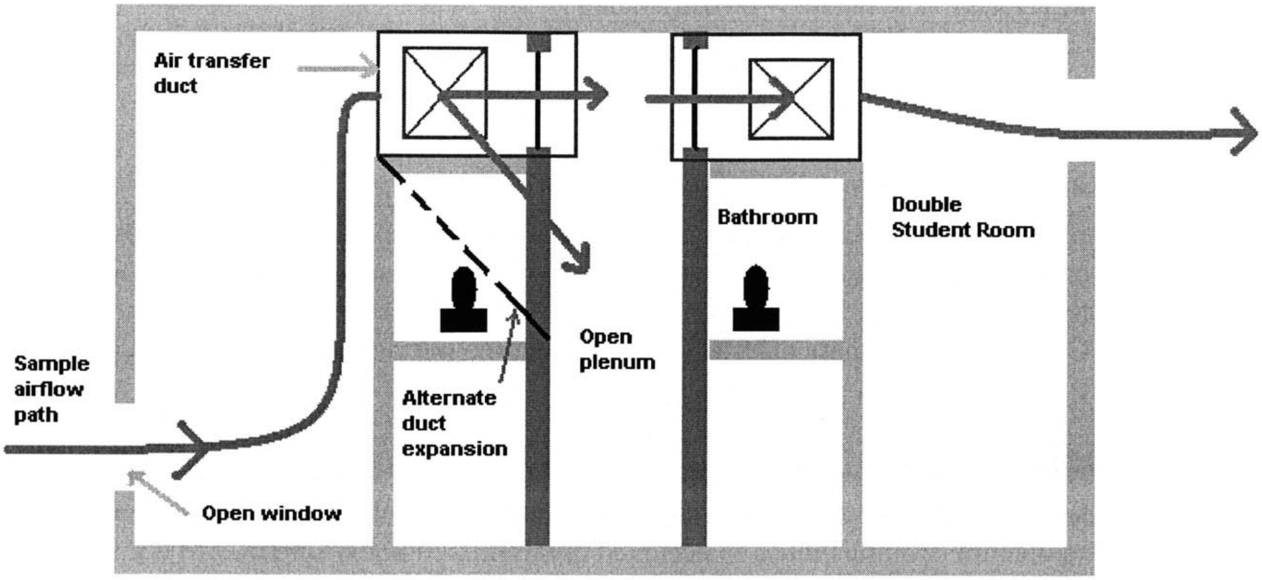


Figure 182 Overhead schematic of open plenum transfer system for cross ventilation. See Figure 181 for the cross-section view of the system.

With an actual duct in place, flow can be better controlled. With an open plenum, a major concern is that the resistance of the air contracting and expanding to get into and out of the plenum space will be too high. With a duct, the constant cross-section will force the air to travel at a constant velocity from one room to the other and hence avoid changes in velocity that can increase turbulence. By avoiding sharp duct entrances and exits, the resistance can be kept to a minimum. If the plenum space is left open, it should be sealed tightly to still behave as a very wide duct. The system should work though, given the calculations. Students should try to open all their windows to minimize losses and achieve maximum ventilation. For days when there is no wind, a fan would aid in achieving 30 air changes an hour. This value is determined to be effective when using natural ventilation as a cooling strategy. The fan used should be sized to run at up to 4,000 cfm, assuming ventilation of four rooms (two singles and two doubles). The fan would be placed above the open plenum as indicated in Figure 181.

Chapter 5 Model Fundamentals

The framework for the model is partially taken from work down as part of the NatVent project described in the background chapter of this thesis. As part of the NatVent project, a Windows-based software program was developed to predict the performance of naturally ventilated buildings. In the model used for this particular thesis research, some further simplifications have been made. Charlotte Svensson and Soren Aggerholm wrote the original NatVent program manual in July of 1998 [Svensson & Aggerholm, 1998].

5.1 Pressure Distribution

The pressure distribution over a building will affect how air will eventually flow through the building. In a naturally ventilated building, air is moved due to wind and thermal effects. The air will move from a location of higher pressure to one of lower pressure.

5.1.1 Wind Pressure

As wind flows around a building, it will create regions of unequal pressure on all of the building surfaces it hits. The shape of this pressure field is determined by the magnitude and direction of the wind, as well as on the shape of the building and its surroundings.

In most cases, a weather station will not be located at a building site. Thus, meteorological wind data should be adjusted based on the characteristics of the terrain between the weather station and the building being modeled.

An empirical model [ASHRAE, 1997] was used as follows:

$$u_{wind,building} = u_{wind,station} \times k_w \times z^{a_w}$$

where:

$u_{wind,station}$ = measured velocity at 10 meters height in open surroundings [m/s]
k_w, a_w = constants dependent on terrain
z = desired height [m]

Description	**Shielding Conditions**	**k_w**	**a_w**
Exposed	Open, flat country	0.68	0.15
Obstructions of ½ building's height	Country with scattered wind breaks	0.52	0.2
Obstructions of building's height	Urban	0.35	0.3

Table 18 Wind coefficients for various types of terrain.

As wind hits a building, it slows down and diverges into separate flow paths. The resultant pressure distribution for every building will be unique. To simplify analysis, a coefficient of pressure is introduced [ASHRAE, 1997]:

$$p_{wind} = \frac{1}{2} \times C_p \times \rho_{air} \times u_{wind}^2 \qquad \text{[Pa]}$$

where:

C_p = pressure coefficient [-]
ρ_{air} = density of air [kg/m^3]
u_{wind} = wind velocity at building site [m/s]

This equation is derived from the Bernoulli equation. The coefficient of pressure determines the magnitude that wind pressure is present on a particular area of a building.

There are significant hurdles in finding pressure coefficients for a building. The coefficients will vary from one building to another; similar to how even the slightest change in curvature of an aircraft wing will affect its overall aerodynamic performance. Finding exact pressure coefficient values requires full-scale measurements, wind tunnel experiments on scaled-down buildings, or extensive computational fluid dynamic techniques. For the model being developed here, using very precise pressure coefficients would go against the need for an easy to use pre-design tool. Thus, averaged pressure coefficient values for standard building configurations are used. They are readily found in standard literature. The values used in this work are included in Appendix G.

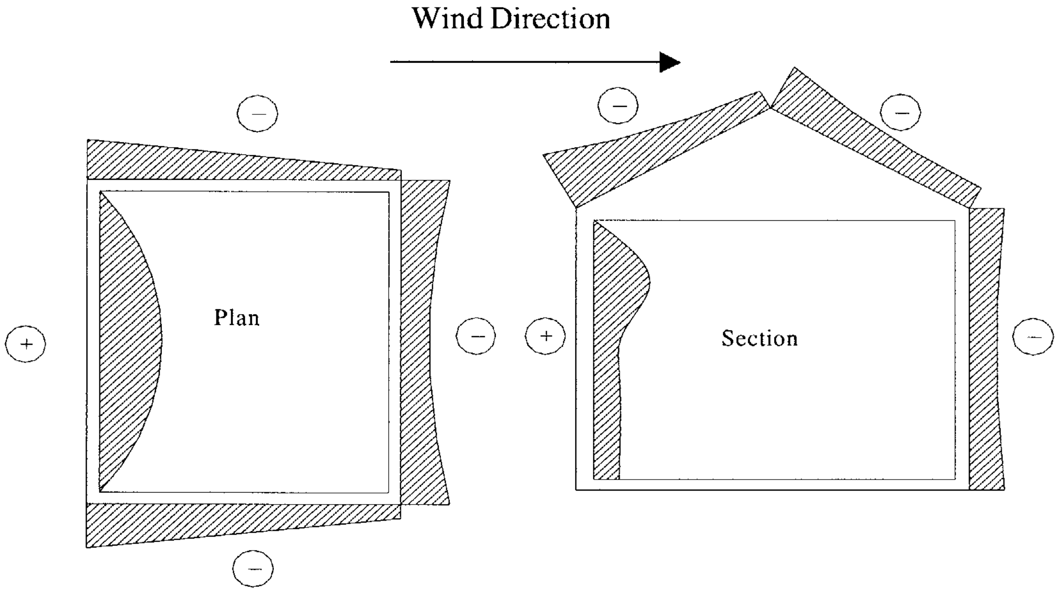


Figure 183 Diagram of wind pressures on a sample building.

5.1.2 Thermal Buoyancy

A thermal pressure gradient can also be generated by a difference in density between hot and cold air. This difference is typically referred to as the stack effect and can be described by the following equation [Duffie & Beckman, 1991]:

$$\Delta p_{thermal} = (\rho_{cold} - \rho_{hot}) \times g \times h \qquad \text{[Pa]}$$

where:

ρ_{cold} = density of the colder air [kg/m^3]
ρ_{hot} = density of the warmer air [kg/m^3]
g = gravitational acceleration = 9.81 [m/s^2]
h = height [m]

The density of air is determined by its temperature and humidity ratio. The density of air at zero degrees Celsius and a relative humidity of 50% is 1.291 kg/m^3. A higher temperature will result in a lower density and vice versa. Over the temperature range that a building will operate at, humidity does not affect the overall air density significantly; thus it is ignored.

5.1.3 Overall Pressure Difference

The overall pressure difference over a building's envelope, due to the thermal and wind effects previously described, can be determined by summing up the individual components.

$$\Delta p_{total} = p_{thermal} + p_{wind} + p_{room} \qquad \text{[Pa]}$$

where:

p_{room} = internal room pressure at ground level [Pa], ref = 0

5.2 Air Flow

Air can flow through a building in several ways. They include infiltration through walls and ceilings, flow through small cracks around windows and doors, controlled flow through open windows and vents, forced flow through ducts and fans, and thermally driven flows through passive stacks. We will ignore infiltration.

5.2.1 Overall Modeling

There are several methods of modeling airflow, ranging from the use of very simple equations to time-consuming computational fluid dynamic (CFD) methods. Two relatively simple methods will be presented here.

5.2.2 ASHRAE Model

The 1997 edition of ASHRAE's fundamentals [ASHRAE, 1997] defines natural ventilation openings as windows, doors, dormer openings, and skylights; roof ventilators; stacks connecting to registers; and specially designed inlet and outlet openings. The ventilation airflow rate required to remove a specific amount of heat from an interior space can be calculated from the following equation:

$$Q = q/c_p\rho(t_i\text{-}t_o) \qquad [\mathrm{m^3/s}]$$

where:

Q = airflow rate required to remove heat, $\mathrm{m^3/s}$
q = rate of heat removal, W
c_p = specific heat of air, J/(kg·K)
ρ = air density, $\mathrm{kg/m^3}$
$t_i\text{-}t_o$ = indoor-outdoor temperature difference, K

There are several factors due to wind that affect the natural ventilation rate for a building; they include average speed, prevailing direction, seasonal and daily variation in speed and direction, and local obstructions such as nearby hills, trees, shrubbery, and buildings. Natural ventilation is typically designed for wind speeds of one-half the seasonal average [ASHRAE, 1997].

The following equation shows the rate of air forced through ventilation inlet openings by wind:

$$Q = C_vAV \qquad [\mathrm{m^3/s}]$$

where:

Q = airflow rate, $\mathrm{m^3/s}$
C_v = effectiveness of openings (C_v is assumed to be 0.5 to 0.6 for perpendicular winds and 0.25 to 0.35 for diagonal winds)
A = free area of inlet openings, $\mathrm{m^2}$
V = wind speed, m/s

Airflow caused by thermal forces is also presented as follows:

$$Q = C_D A\sqrt{2g\Delta H_{NPL}(T_i - T_o)/T_i}$$

where:

Q = airflow rate, $\mathrm{m^3/s}$
C_D = discharge coefficient for opening
ΔH_{NPL} = height from midpoint of lower opening to NPL, m
T_i = indoor temperature, K
T_o = outdoor temperature, K

The above equation applies when $T_i > T_o$. When $T_i < T_o$, T_i in the denominator is replaced with T_o, and $(T_i\text{-}T_o)$ is replaced with $(T_o\text{-}T_i)$ in the numerator. If there is thermal stratification in the interior, an average temperature should be used. When there is more than one opening, $C_D = 0.65$

is assumed. A discussion of airflow characteristics through windows is provided by Heiselberg and others [Heiselberg, 1999].

5.2.3 British Standard Method

The British Standard Method is based on empirical data and used to predict ventilation rates in single-zone buildings [Santamouris and Asimakopoulous, 1996]. The method assumes two-dimensional flow through a building and ignores all interior obstructions. The method provides formulas for both single-sided and cross ventilation cases.

For wind-driven single-sided ventilation with one opening:

$$Q = 0.025AV$$

where:

Q = volumetric flow rate, m^3/s
A = opening area, m^2
V = wind velocity, m/s

For ventilation caused by a temperature difference in a space with two openings at different heights:

$$Q = C_D A\left[\frac{\varepsilon\sqrt{2}}{(1+\varepsilon)\left(1+\varepsilon^2\right)^{\frac{1}{2}}}\right]\left(\frac{\Delta T g H_1}{\bar{T}}\right)^{\frac{1}{2}}$$

where:

$\varepsilon = A_1/A_2$, dimensionless
$A = A_1 + A_2$, m^2
C_d = discharge coefficient

For ventilation caused by a temperature difference with only one opening:

$$Q = C_D \frac{A}{3}\sqrt{\frac{\Delta T g H_2}{\bar{T}}}$$

With the buildings being studied, cross ventilation is the dominant ventilation strategy. For wind-driven cross ventilation:

$$Q_w = C_d A_w V \sqrt{\Delta C_p}$$

$$\frac{1}{A_w^2} = \frac{1}{(A_1 + A_2)^2} + \frac{1}{(A_3 + A_4)^2}$$

where:

ΔC_p = Difference in pressure coefficients between windward and leeward building faces
A_1 = Upper opening on windward side, m^2
A_2 = Lower opening on windward side, m^2
A_3 = Upper opening on leeward side, m^2
A_4 = Lower opening on leeward side, m^2

For ventilation driven by temperature differences, the British Standard Method is the same as the method specified by ASHRAE.

We combine the overall ventilation caused by both wind and temperature differences by the following:

$Q = Q_{temperature}$

$\quad$ for $V/(\Delta T)^{0.5} < 0.26(A_b/A_w)^{0.5}(H_l/\Delta C_p)^{0.5}$

$Q = Q_w$

$\quad$ for $V/(\Delta T)^{0.5} > 0.26(A_b/A_w)^{0.5}(H_l/\Delta C_p)^{0.5}$

where:

$\Delta T = T_{in}-T_{out}$

H_l = difference in height between upper and lower openings, m

The British standard method is the final airflow model used in calculations. The reason for this is that the model specifies the use of averaged wall pressure coefficients. The use of pressure coefficients is a step above the simplicity of the ASHRAE model, which does not directly take into account wind direction.

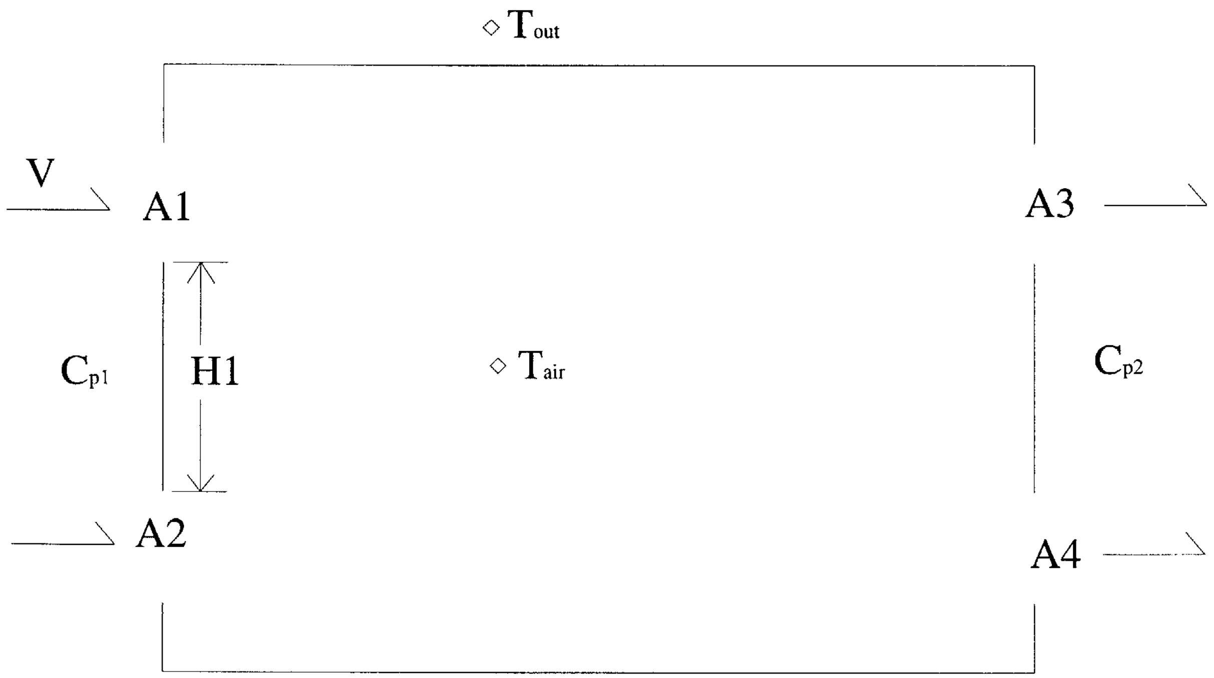


Figure 184 Diagram of British Standard Method parameters, for cross ventilation. (Adapted from Santamouris and Asimakopoulous (1996)).

5.3 Thermal Model

5.3.1 General Theory

We are primarily interested in thermal conditions during the cooling season and thus formulate a model tailored to this. The heat balance and indoor temperature are calculated every ten minutes using a single time constant model. In the model it is assumed that all internal surfaces have the same temperature. The heat balance and the indoor air temperature that are calculated represent an average value for the building.

The heat transferred to the indoor air is calculated first. We neglect the heat exchange between the indoor air and interior surfaces:

$$Q_{air} = Q_{in} + Q_{fenestration} + Q_{wall} + Q_{ventilation}$$

where:

Q_{in} = internal heat gains, W
$Q_{fenestration}$ = heat transfer through windows, including solar radiation, W
Q_{wall} = heat transfer through walls, including solar radiation, W
Q_{vent} = heat transfer by ventilation, W

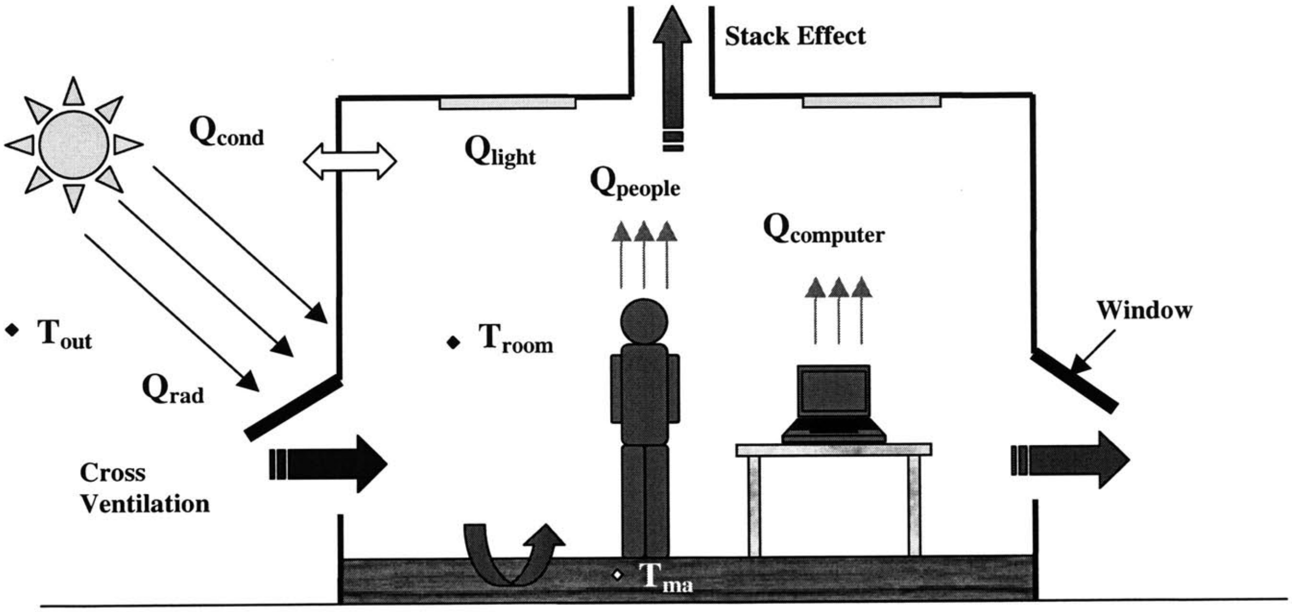


Figure 185 Diagram of key parameters included in thermal model.

The indoor air temperature at time t is calculated using the internal surface temperature from the previous time step:

$$T_{air}(t) = T_{mass-1} + Q_{air}/h_{conv}A_{conv}$$

where:

T_{mass-1} = internal surface temperature at the previous time step, K
Δt = length of each time step, s
Q_{air} = heat transfer to the indoor air (neglecting radiation between surfaces), W
h_{conv} = heat transfer coefficient between indoor air and internal surfaces, W/m^2K
A_{conv} = area of convection between internal surfaces and indoor air, m^2

The model assumes an h-value of 7 W/m^2K. While this value is typically around 3 W/m^2K in a mechanically ventilated building, we use a higher value given the higher air exchange rate typically found in a naturally ventilated building.

The heat transfer from the indoor air to the internal surfaces is:

$$Q_{mass} = h_{conv} \times A_{conv} \times (T_{mass-1} - T_{air-1})$$

where:

Q_{mass} = resultant heat transfer to internal surfaces/thermal mass, W
T_{air-1} = temperature of interior air at the previous time step, K

Using the above, we see:

$$T_{mass} = T_{mass-1} - \frac{h_{conv}A_{conv}(T_{mass-1} - T_{room-1})\Delta t}{m_{mass}c_{mass}}$$

where:

m_{mass} = mass of internal surfaces available as thermal mass, kg
c_{mass} = heat capacity of thermal mass, J/kg K

By completing the mass balance, we arrive at a relation for the room temperature

$$T_{air}(t) = \frac{Q_{air} + Q_{vent}\rho_{air}c_pT_{out} + h_{conv}A_{conv}T_{mass}}{Q_{vent}\rho_{air}c_p + h_{conv}A_{conv}}$$

where:

ρ_{air} = density of air at 20 °C, kg/m^3
c_p = heat capacity of air, J/kg K
T_{out} = outdoor air temperature, K

The transient version of the above equation is based on a first-order ordinary differential equation [Allard, 1998]:

$$\rho_{air} c_p V \frac{dT_{air}}{dt} = Q_{air} + \dot{m} c_p T_{out} - \dot{m} c_p T_{air} + h_{conv} A_{conv} (T_{mass} - T_{air})$$

where:

$\dot{m}$ = mass flow rate of outdoor air through interior space, kg/s
V = volume of single-zone, m^3

The solved differential equation is:

$$T_{air}(t) = \frac{Q_{air} + \dot{m} c_p T_{out} + h_{conv} A_{conv} T_{mass}}{\dot{m} c_p + h_{conv} A_{conv}} + \left[T_i - \frac{Q_{air} + \dot{m} c_p T_{out} + h_{conv} A_{conv} T_{mass}}{\dot{m} c_p + h_{conv} A_{conv}} \right] e^{-\left(\frac{\dot{m}}{\rho_{air} V} + \frac{h_{conv} A_{conv}}{\rho_{air} c_p V} \right) t}$$

where: $T_{mass} = (T_i - T_{out}) e^{-\left(\frac{h_{conv} A_{onvs}}{\rho V c} \right) t} + T_{out}$

T_i = initial temperature at time step, t = 0, K
c = heat capacity of thermal mass, J/kg K
ρ = density of thermal mass, kg/m^3

5.3.2 Determination of internal heat gains

The gains from lighting, occupants, appliances, computers, and other office equipment were accounted for in each space. Internal heat gains during non-working hours were assumed to be 20% of the heat gains generated during working hours. Internal heat gains form an important part of both the interior surface energy balance, in the form of radiation, and of the zone air energy balance, in the form of convection [Mcquiston, Parker & Spitler, 2001]. To simplify this model, it is assumed that all internal heat gains contribute directly to the zone air energy balance. It will be accepted that errors will result from this simplification. In the future, a method such as the radiant time series method [ASHRAE, 2001a] could be used for better accuracy. A listing of gains for each building studied is presented in their respective results chapters.

5.3.3 Building heat transmission

Heat transmission through external walls, windows, and the roof was calculated based on each component's insulation thickness and an average outdoor convection coefficient. To account for the effect of solar radiation, a sol-air temperature was employed [McQuiston et al., 2001]:

$$Q_{wall} = U_{overall} \times A_{wall} \times (T_{sol\text{-}air} - T_{air})$$

where:

$U_{overall}$ = transmission coefficient through surface including effect of outdoor convection, $W/m^2\,K$
A_{wall} = area of wall exposed to outdoors, m^2
$T_{sol\text{-}air}$ = sol-air temperature, K

The overall U-value is:

$$U_{overall} = \frac{1}{\frac{1}{h_{ext}} + \frac{1}{U_{wall}}}$$

where:

h_{ext} = external surface heat transfer coefficient (~ 10 $W/m^2\,K$ for summer conditions)
U_{wall} = wall U-value based on insulation thickness, $W/m^2\,K$

The sol-air temperature is the temperature of outdoor air that, in the absence of radiation changes, gives the same rate of heat entry into the surface as would the combination of incident solar radiation, radiant energy exchange with the sky and other outdoor surroundings, and convective heat exchange with the outdoor air [ASHRAE, 1997].

$$T_{sol\text{-}air} = T_{out} + \alpha I_t / h_o - \varepsilon \Delta R / h_o$$

where:

α = absorptance of surface for solar radiation
I_t = total solar radiation incident on surface, W/m^2
h_o = coefficient of heat transfer by long-wave radiation and convection at out surface, W/m^2K
T_{out} = outdoor air temperature, K
$\varepsilon \Delta R / h_o$ = long-wave radiation factor = -3.9 °C for horizontal surfaces, 0 °C for vertical surfaces

5.3.4 Solar Radiation

Solar Position

The model calculates solar radiation assuming clear sky conditions, with a user-option to account for cloud cover. When calculating solar radiation on a particular surface in a given location, the position of the sun must be known. The standard of timekeeping used is known as apparent solar time (AST) [ASHRAE, 1997]:

$$AST = LST + EOT + 4(LSM-LON)$$

where:

LST = local standard time
EOT = equation of time, min
LSM = local standard meridian, degree of arc
LON = local longitude, degrees of arc
4 = minutes of time required for one degree rotation of earth

The local standard meridian for Eastern Standard Time is 75°. The equation of time can be found from the following [McQuiston et al., 2001]:

$$EOT = 229.2\,(0.000075 + 0.001868 \cos N - 0.032077 \sin N - 0.014615 \cos 2N - 0.04089 \sin 2N)$$

where:

$N = (n-1)(360/365)$
n = Julian Day, day of the year, $n = 1$ (January 1st), $n = 365$ (December 31st)

We describe the direction of the sun's rays by the latitude, the hour angle, and the sun's declination in Figure 186. The latitude l is the angle between the line OP and the projection of OP on the equatorial plane. The hour angle h is the angle between the projection of P on the equatorial plane and the projection of that plane on a line from the center of the sun to the center of the earth. The sun's declination d is the angle between a line connecting the center of the sun and earth and the projection of that line on the equatorial plane [McQuiston et al., 2001].

The declination in degrees can be found using the following equation:

$$\delta = 0.39673723 - 22.9132745 \cos N + 4.0254304 \sin N - 0.3872050 \cos 2N + 0.05196728 \sin 2N - 0.1545267 \cos 3N + 0.08479777 \sin 3N$$

where:

N = Julian day

For building related calculations, we use the solar altitude β, the sun's zenith angle ψ, the solar azimuth ϕ, and the wall solar azimuth γ, to determine the sun's angle of incidence θ, on the building surface we are interested in.

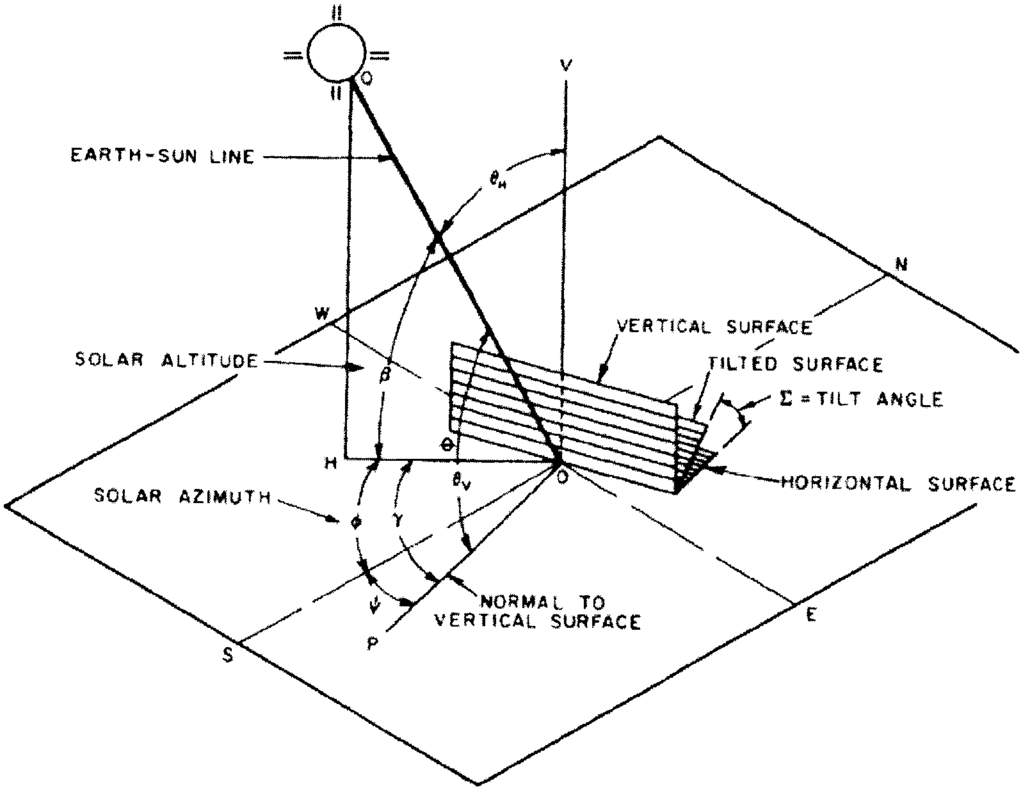


Figure 186 Diagram of parameters related to solar radiation. (Source: ASHRAE Fundamentals, 1997)

$$\sin\beta = \cos l \cosh \cos d + \sin l \sin d$$

$$\cos\phi = \frac{\sin\beta \sin l - \sin d}{\cos\beta \cos l}$$

$$\gamma = \phi \pm \psi$$

$$\cos\theta = \cos\beta \cos\gamma \sin\alpha + \sin\beta \cos\alpha$$

where:

α = angle of tilt between the normal to the surface and the normal to the horizontal surface.

Clear Sky Model

The value of the solar irradiation at the surface of the earth on a clear day, is given by the ASHRAE clear sky model as [ASHRAE, 1997]:

$$G_{ND} = \frac{A}{\exp(B / \sin \beta)}$$

where:

G_{ND} = normal direction irradiation, W/m^2
A = apparent solar irradiation at air mass equal to zero, W/m^2
B = atmospheric extinction coefficient
β = Solar altitude

The diffuse radiation falling on a horizontal surface is given by the use of a factor C, which is the ratio of diffuse irradiation on a horizontal surface to direct normal irradiation:

$$G_d = (C)(G_{ND})$$

The direct radiation falling on a surface of any orientation, corrected for clearness is:

$$G_D = C_N G_{ND} \cos \theta$$

where:

θ = angle of incidence between the sun's rays and the normal to the surface.

The diffuse radiation striking a non-horizontal surface on a clear day is given by the following:

$$G_{d\theta} = CG_{ND}F_{ws}$$

where:

F_{ws} = view factor between the wall and sky, $F_{ws} = \frac{1 + \cos \Sigma}{2}$, Σ = tilt angle of surface from horizontal.

The total irradiation on a surface is the sum of the diffuse and direct components of radiation:

$$G_t = G_d + G_D$$

Values for A, B, and C are given in the following table:

	Equation of Time, min.	Declination, degrees	A W/m^2	B Dimensionless	C
January	-11.2	-20.0	1230	0.142	0.058
February	-13.9	-10.8	1215	0.144	0.060
March	-7.5	0.0	1186	0.156	0.071
April	1.1	11.6	1136	0.180	0.097
May	3.3	20.0	1104	0.196	0.121
June	-1.4	23.45	1088	0.205	0.134
July	-6.2	20.6	1085	0.207	0.136
August	-2.4	12.3	1107	0.201	0.122
September	7.5	0.0	1151	0.177	0.092
October	15.4	-10.5	1192	0.160	0.073
November	13.8	-19.8	1221	0.149	0.063
December	1.6	-23.45	1233	0.142	0.057

Table 19 Average monthly values for determining solar radiation. (Source: ASHRAE Fundamentals, 1997)

5.4 Fenestration

Fenestration refers to any glazed opening in a building envelope. The components of fenestrations include: glazing material, framing, external, in-glazing, and internal shading devices. The total heat transmission through glass is equal to the radiation transmitted through the glass, the inward flow of absorbed solar radiation, and the heat gain due to conduction [ASHRAE, 1997].

In the model, we use simplified solar heat gain calculations using solar heat gain factors (SHGF). The term takes into account the combined effects of both transmitted solar heat gain and absorbed solar heat gain conducted into a space [McQuiston et at., 2001].

The transmitted solar heat gain factor is:

$$TSHGF = G_D \sum_{j=0}^{5} t_j [\cos\theta]^j + 2G_d \sum_{j=0}^{5} \frac{t_j}{j+2}$$

The absorbed solar heat gain factor is:

$$ASHGF = G_D \sum_{j=0}^{5} a_j [\cos\theta]^j + 2G_d \sum_{j=0}^{5} \frac{a_j}{j+2}$$

The coefficients for double-strength sheet glass (DSA) are given in the following table:

J	**a_j**	**t_j**
0	0.01154	-0.00885
1	0.77674	2.71235
2	-3.94657	-0.62062
3	8.57811	-7.07329
4	-8.38135	9.75995
5	3.01188	-3.89922

Table 20 Values for calculating solar heat gain factors for DSA. (Source: ASHRAE Fundamentals, 1997)

The actual transmitted solar heat gain is given by:

TSHG = (SC)(TSHGF)

The actual absorbed solar heat gain is given by:

ASHG = (SC)(ASHGF)(N_i)

where:

SC = shading coefficient, the ratio of solar fenestration heat gain to the solar heat gain of DSA glass.

$$N_i = \frac{h_i}{h_i + h_o} = 0.267$$

The instantaneous solar heat gain is:

SHG = TSHG + ASHG

Values for the shading coefficient are available for many different configurations of glazing units combined with internal shading such as Venetian blinds and roller shades. The SC is not appropriate in accounting for the effect of external shading.

5.4.1 External Shading

Fenestrations can be shaded by a combination of roof overhangs, other buildings, trees, shrubbery, and side fins. External shading can reduce solar gains by up to 80 percent [McQuiston et at., 2001]. The shadow width S_W and shadow height S_H, produced by the vertical and horizontal projections (P_V and P_W), respectively, can be calculated using the solar surface azimuth γ and the horizontal profile angle Ω. We assume that any shaded portion of a building has no direct solar gain.

The profile angle can be calculated with the following equations [ASHRAE, 1997]:

$$\tan \Omega = \tan \beta / \cos \gamma$$

The shading provided is then given by:

$$S_W = P_V |\tan \gamma|$$
$$S_H = P_H \tan \Omega$$

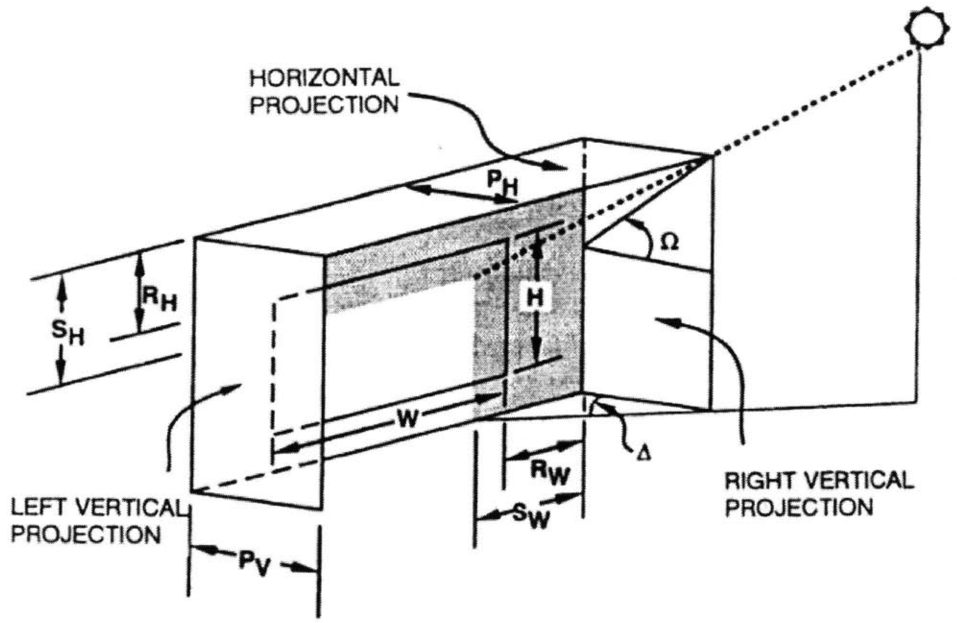


Figure 187 Geometric relationships for determining shading given by horizontal and vertical projections. (Source: ASHRAE Fundamentals, 1997)

5.5 Thermal Comfort

5.5.1 Fanger Model

There are several thermal comfort indices and charts that can be used to predict thermal comfort. Until very recently, all of the currently available prediction material for thermal comfort was based on an environment using active mechanical ventilation. In 1972, P.O. Fanger published a book describing a still often used method of determining thermal comfort [Fanger, 1972]. The model is part of ISO standard 7730 of 1995, "Moderate Thermal Environments-Determination of the PMV and PPD indices and specification of the conditions for thermal comfort."

Thermal comfort is determined as "that condition of mind which expresses satisfaction with the thermal environment [INNOVA, 1996]." The core temperature of the human body is regulated to approximately 37 °C by dozens of different mechanisms, such as shivering and sweating [ISO, 1995]. The Fanger comfort equation is based on an equation for comfortable skin temperature and sweat production combined with the equation for the body's energy balance according to the first law of Thermodynamics.

Thermal comfort is determined by four environmental parameters and two personal parameters. The environmental parameters are mean radiant temperature, dry bulb temperature, humidity, and air speed. The personal parameters are clothing insulation level and activity level. These parameters serve as inputs to the following human body energy equation [Chen, 2001]:

$M\text{-}W = Q_{sk} + Q_{res} = (C_{sk} + R_{sk} + E_{sk}) + (C_{res} + E_{res})$

where:

- M = Rate of metabolic heat production (W/m^2 body surface area)
- W = Rate of mechanical work
- Q = Heat losses
- C = Convective losses
- R = Radiative heat losses
- E = Evaporative heat losses
- sk = Skin
- res = Respiration

A further breakdown results in the following individual relationships [Chen, 2001]:

W = active work and shivering (involuntary work) [W/m^2 body area]
M = rate of metabolic heat production [W/m^2]
$C_{sk} = h_c\,(T_{cloth}\text{-}T_{air})\,A_{cloth}\,/A_{body}$ [W/m^2]

$h_c = 2.38\,(T_{cloth}\text{-}T_{air})^{0.25}$ when $2.38\,(T_{cloth}\text{-}T_{air})^{0.25} > 12.1\,V^{0.5}$
$h_c = 12.1\,V^{0.52}$ when $2.38\,(T_{cloth}\text{-}T_{air})^{0.25} < 12.1\,V^{0.5}$

$$T_{cloth} = 35.7 - 0.0275\,(M - W) - R_{cloth}\{(M - W) - 3.05\,[\,5.73 - 0.007\,(M - W) - p_v\,] - 0.42\,[(M - W) - 58.15] - 0.0173\,M\,(5.87 - p_v) - 0.0014\,M\,(34 - T_{air})$$

p_v = vapor pressure (kPa)

$A_{body} = 0.202\,m^{0.425}\,l^{0.725}$ [m^2]

m = body weight [kg]
l = height [m]

A_{cloth}/A_{body} = f (garment insulation value) = $1.0 + 0.3\,I_{cl}$

R_{cloth} = cloth thermal resistance (m^2K/W)
$R_{cloth} = 0.155 I_{cl}$ (1 clo = 0.155 m^2K/W)

$R_{sk} = 3.96\text{x}10^{-8}\,[(T_{cloth} + 273)^4 - (T_{enclosure} + 273)^4]\,A_{cloth}/A_{body}$ [W/m^2]

$E_{sk} = m_{sk} i_{fg} = 3.05\,[5.73 - 0.007\,(M - W)\text{-}p_v] + 0.42[(M - W) - 58.15]$

$C_{res} = m_{res} C_{p,a}(T_{res} - T_{air}) = 0.0014\,M\,(24 - T_{air})$

$E_{res} = m_{res} i_{fg}$

$L = M - W\text{-}\,[(C_{sk} + R_{sk} + E_{sk}) + (C_{res} + E_{res})]$

PMV (predicted mean vote) = $[0.303\,\exp(-0.036\,M) + 0.028]\,L$
PPD (predicted percentage dissatisfied) = $100 - 95\,\exp[-(0.03353\,PMV^4 + 0.2179\,PMV^2)]$

The predicted mean vote is a prediction of the overall average thermal sensation people will feel, given a particular set of environmental conditions. The predicted percentage dissatisfied gives an indication of the number of people that will be dissatisfied with those environmental conditions.

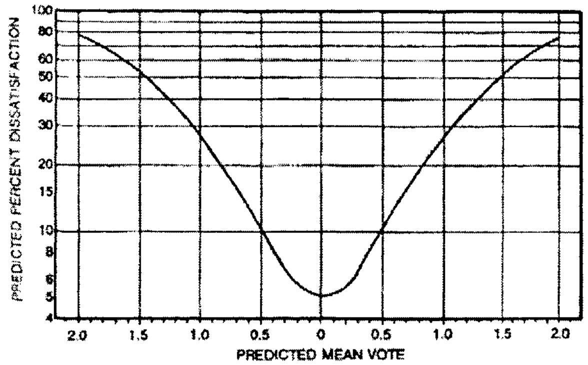


Figure 188 Predicted percentage of dissatisfied (PPD) as function of predicted mean vote.

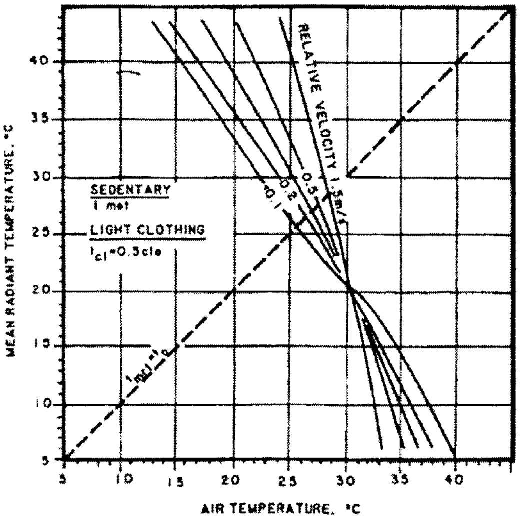


Figure 189 Air temperature and mean radiant temperature necessary for comfort (PMV = 0) of sedentary persons in summer clothing at 50% relative humidity. Source: ASHRAE Fundamentals, 1997.

The enclosure temperature is also commonly referred to as the mean radiant temperature. It turns out that the Fanger model is very sensitive to this value. Enclosure temperature presents a challenge to building engineers that is often overlooked.

$T_{mrt} = \Sigma A_i T_i / \Sigma A_i$

where:

T_i = surface temperature of enclosure $_I$
A_i = area of surface i

5.5.2 ASHRAE Comfort Zone

The ASHRAE comfort zone is in some sense easier to use than the Fanger model, because it is based on a single psychrometric chart with a pre-delineated zone. The Fanger model requires computer computation, but gives better control over input parameters. The ASHRAE comfort zone is plotted based on two separate variables, effective temperature and operative temperature. Effective temperature is the temperature at a relative humidity of 50% where body heat loss is the same as in an actual environment. This index effectively combines temperature and humidity into one value. Operative temperature equals 0.45 T_{air} + 0.55 T_{mrt} and combines an enclosure temperature with the indoor dry bulb temperature. The version used in our analysis relies on the operative temperature.

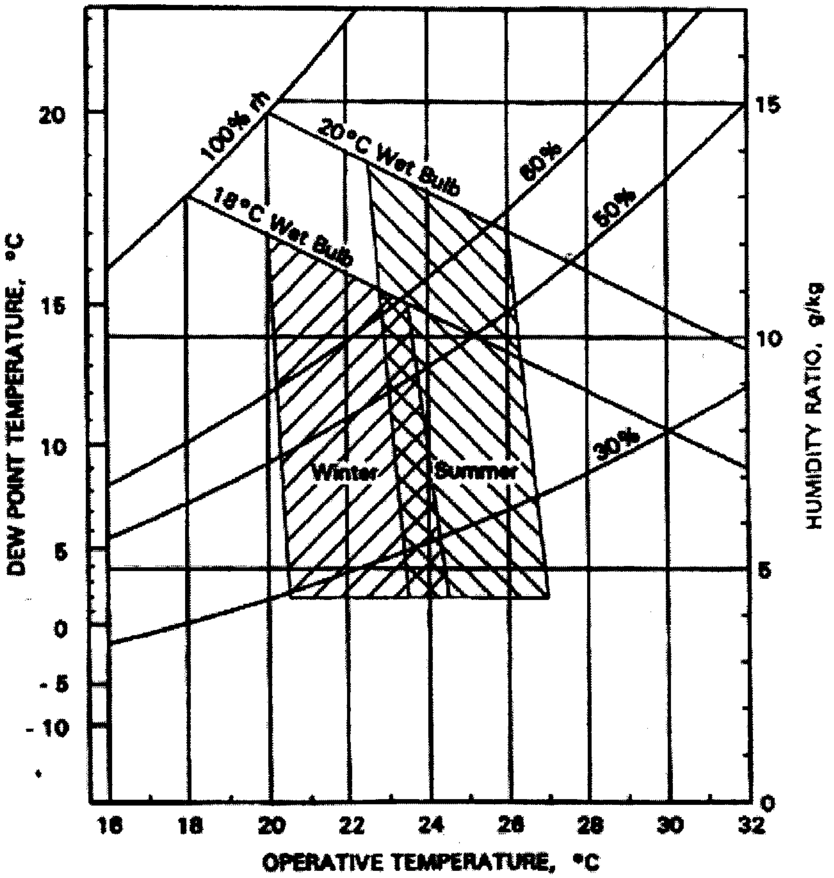


Figure 190 ASHRAE summer and winter comfort zones based on acceptable ranges of operative temperature humidity for people in typical summer and winter clothing during primarily sedentary activity. Source: ASHRAE Fundamentals, 1997.

5.5.3 Draft

The ISO 7730 standard also provides a method to predict the percentage of dissatisfied people due to drafts. Drafts tend to be among the most common complaint regarding the indoor climate in buildings. Discomfort due to drafts is the result of localized heat loss on typically unclothed portions of the body. The turbulence intensity, the degree of fluctuation of the air, plays a major role in the disturbance of a draft.

The ISO 7730 equation is as follows [ISO, 1995]:

$$DR = (34 - T_{air})(V_a - 0.05)^{0.62}(37\ SD + 3.14)$$

where:

DR = draft rating [%]
T_{air} = air temperature [°C]
V_a = local mean air velocity [m/s]
SD = standard deviation of air velocity [m/s]

The turbulence $Tu = 100\ SD/v_a$

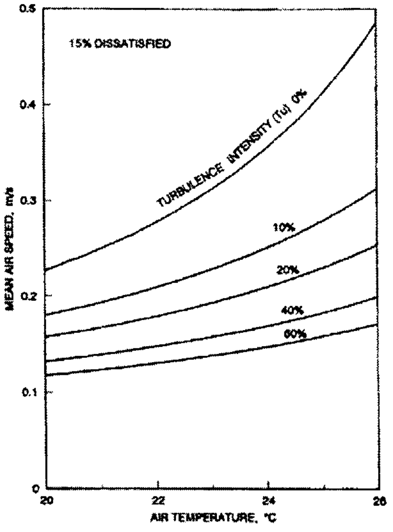


Figure 191 Draft conditions dissatisfying 15% of the population.

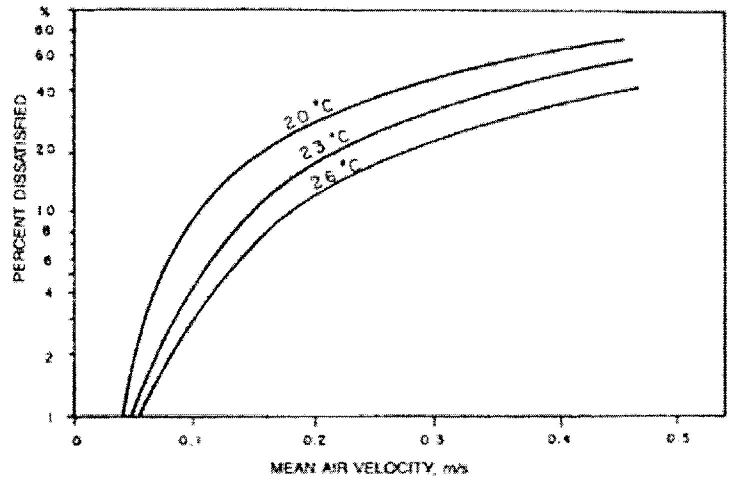
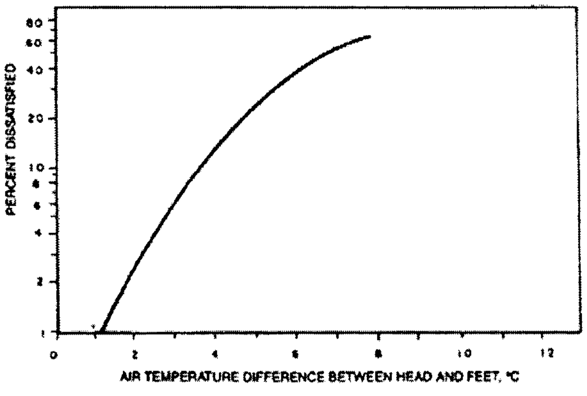


Figure 192 Percentage of people dissatisfied as function of mean air velocity. Source: ASHRAE Fundamentals, 1997.

5.5.4 Thermal Radiation Asymmetry and Vertical Air Temperature Gradient

As was mentioned before, the enclosure temperature in a space plays an important role in determining a person's thermal comfort. Variations in surface temperature—a very cold floor with a very warm ceiling—can lead to thermal discomfort. Charts are presented below. On a related note, the ISO 7730 standard specifies that floor temperatures of 19°C to 29°C are acceptable to people with sedentary activity with a maximum 10% PPD [ISO, 1995].

Typically, people prefer warm feet with a cool head. If this is reversed, thermal discomfort can occur. The ISO 7730 standard specifies that the vertical air temperature difference between head and feet should be no larger than 3°C to achieve a maximum 5% PPD [ISO, 1995].



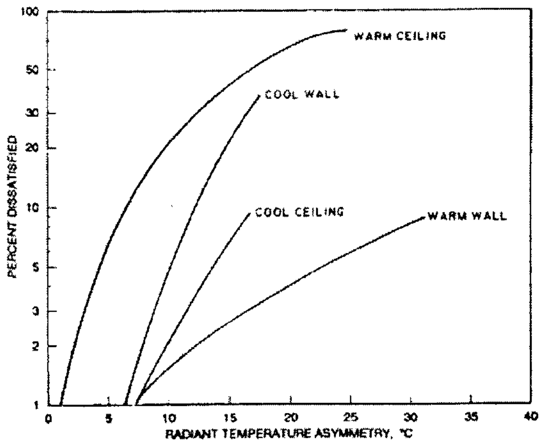


Figure 193 Percentage of people dissatisfied as function of vertical air temperature difference between head and ankles.

Figure 194 Percentage of people expressing discomfort due to asymmetric radiation. Source: ASHRAE Fundamentals, 1997.

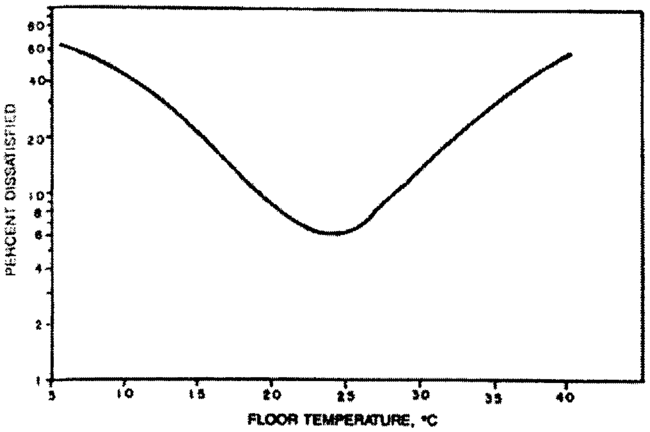


Figure 195 Percentage of people dissatisfied as function of floor temperature. Source: ASHRAE Fundamentals, 1997

Chapter 6 Broadmoor Results and Discussion

There were two original intents with this research: to investigate the thermal comfort of workers in each of the buildings studied, and to determine the performance of a simple thermal-fluids model in predicting indoor space temperatures. An analysis of thermal comfort will be presented first. The model will then be discussed, as applied to each building with real weather conditions.

6.1 Broadmoor Summary

In many ways, the Broadmoor Wildlife Sanctuary's nature center is a huge success story. For almost two decades, the building has provided a comfortable environment for full-time workers, as well as thousands of visitors that visit each year, without the use of any active mechanical system. Interviews with staff members indicate that the building's greatest asset is the availability of abundant amounts of natural daylight and air. On the warmest of days, workers do feel the building is too warm. This is overcome by drinking plenty of fluids, moving to the cooler basement space for a break, using personal desk fans, and dressing lightly.

Staff members were asked to recount comments from visitors. On a whole, they have been extremely positive and focused around the overall comfort of the building. The majority of negative comments focused around odors from the composting toilets. When the building is closed up during a long weekend, the toilets can release significant amounts of odors. These odors quickly dissipate when a dose of peat moss is added to the toilets.

When asked to compare their experience working in the building to working in an air-conditioned building, all stated they preferred having the option to open windows. None felt the need to install air-conditioning in the building; they had adapted to the occasional times when the building is too warm.

6.2 Data Analysis

6.2.1 Summary of Natural Ventilation Use

Because the Broadmoor building features a basement structure with high thermal mass, as well as a highly insulated building envelope, the building does not swing in indoor temperature as highly as external temperatures. For purposes of analysis, general occupied hours are Tuesday through Sunday from 8 am until 6 pm. Full-time natural ventilation, using an attic vent and louvered doors, began the first week of June. Data from June 12, 2001, onward, was analyzed. On September 26, the louvered doors to the building were shut and locked for the season. On October 16, the attic windows and stack vent were shut. A breakdown of the average measured main floor interior temperature is presented in the following chart:

Temperature Range	Frequency	Approximate Total Hours
$T_{in} < 20°C$ db	8.06%	78
$20°C < T_{in} < 25°C$	53.39%	515
$25°C < T_{in} < 27°C$	21.08%	187
$T_{in} > 27°C$	17.46%	169

Table 21 Summary of average indoor temperatures from June 12, 2001-September 25, 2001.

From a thermal comfort standpoint, we can view dry bulb temperatures between 20 and 25°C as being a standard comfort range based on the standard ASHRAE comfort zone (Figure 190). Between 25 and 27°C, we have an extended comfort zone that assumes a relative humidity below 60%. Above 27°C, we assume that thermal discomfort begins in earnest. Thus, we see that the building would *appear* to maintain comfortable temperatures for occupants for the majority of the time, even when older thermal comfort standards are applied.

In order to achieve an indoor temperature of 75°F (23.9°C) with a relative humidity of 50%, the following conditions, for various air change rates, must be met. We see that at low air change rates, an extremely low temperature is needed. The reason for this is the low overall air volume of the space. In the Philip Merrill Environmental Center, high ceilings provide a buffer of extra room volume to compensate for higher heat loads. The outdoor relative humidity does not appear to be as critical as the dry bulb temperature.

Indoor Temp	In RH	Sensible Heat Load	Latent Heat Load	ACH	Outdoor Temp	Out RH
75 °F (23.9 °C)	60	25,591 Btu/h (7,500 W)	540 Btu/h (160 W)	1	-0.96 °F (-0.53 °C)	≥100
75	60	25,591	540	2	37.00 (2.78)	≥100
75	60	25,591	540	5	59.80 (15.4)	100
75	60	25,591	540	10	67.40 (19.7)	95
75	60	25,591	540	30	72.50 (22.5)	85

Table 22 Required outdoor temperature and humidity conditions for various air change rates per hour.

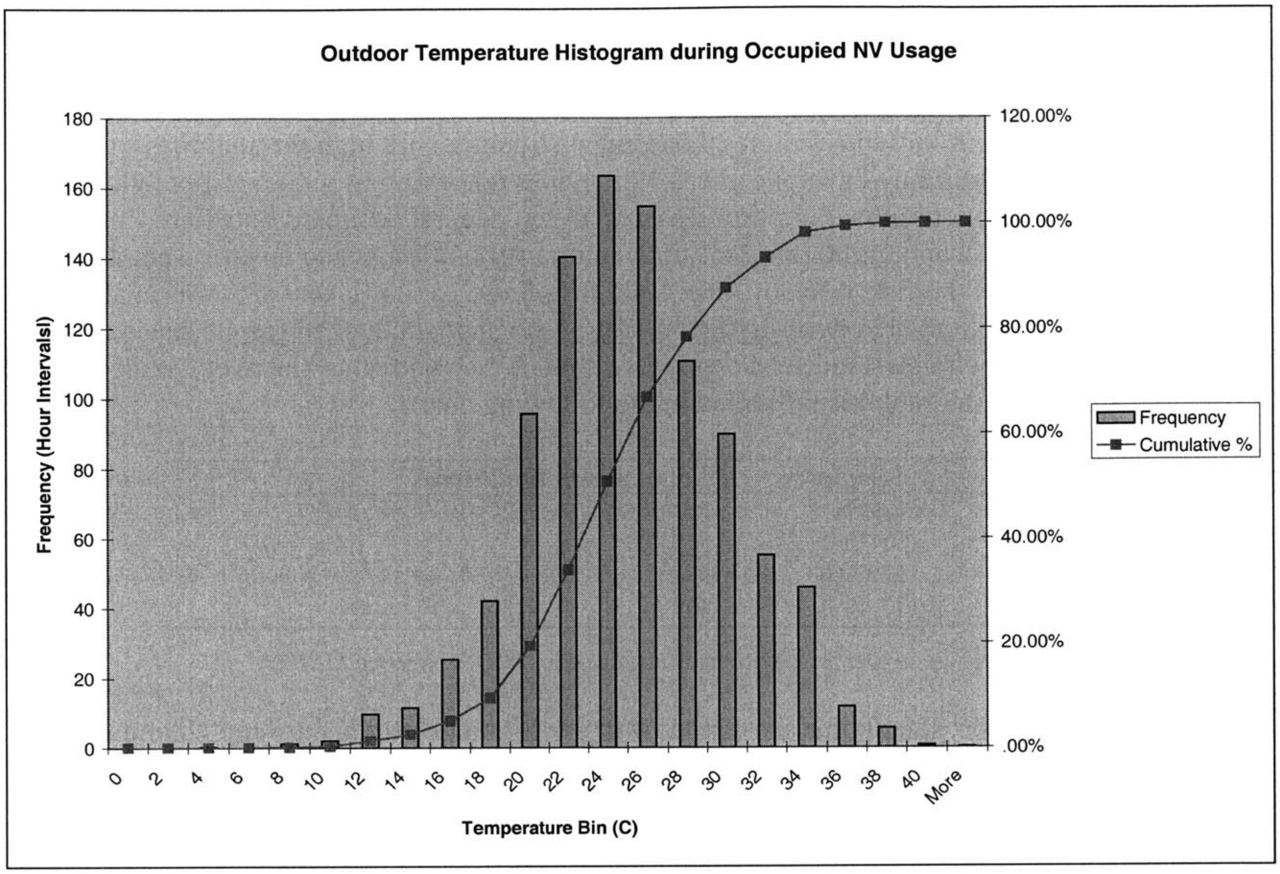


Figure 196 Outdoor temperature histogram for occupied hours between June 12 and September 25, 2001.

6.2.2 Energy Analysis

Since the Broadmoor building does not use any active ventilation system, it enjoys very low annual energy consumption. An analysis of the potential chiller energy required between June 12, 2001 and September 25, 2001, the period when natural ventilation was fully utilized, is shown below. The analysis assumes that the building is tight and does not account for fan or pump energy.

We can relate the steady state sensible heat gain to the required outdoor temperature through the following equation [Chen, 2002]:

$$T_o = T_i - \frac{Q_{sensible}}{\rho V C_p}$$

where:

ρ = density of air [kg/m^3]
V = room volume * air changes per hour (ACH) / 3600 [m^3/s]
$Q_{sensible}$ = internal sensible gain from equipment, lighting, solar radiation, wall conduction, and people [W]
C_p = heat capacity of air [J/kg °C]
T_i = desired indoor dry bulb temperature [°C]
T_o = required outdoor dry bulb temperature [°C]

To find the required outdoor humidity, we use the following equation [Chen, 2001]:

$$i_o = i_i - \frac{Q_{total}}{\rho V}$$

where:

Q_{total} = total sensible and latent heat load [W]
i_i = enthalpy at interior state [J/kg dry air]
i_o = enthalpy at required outdoor state [J/kg dry air]

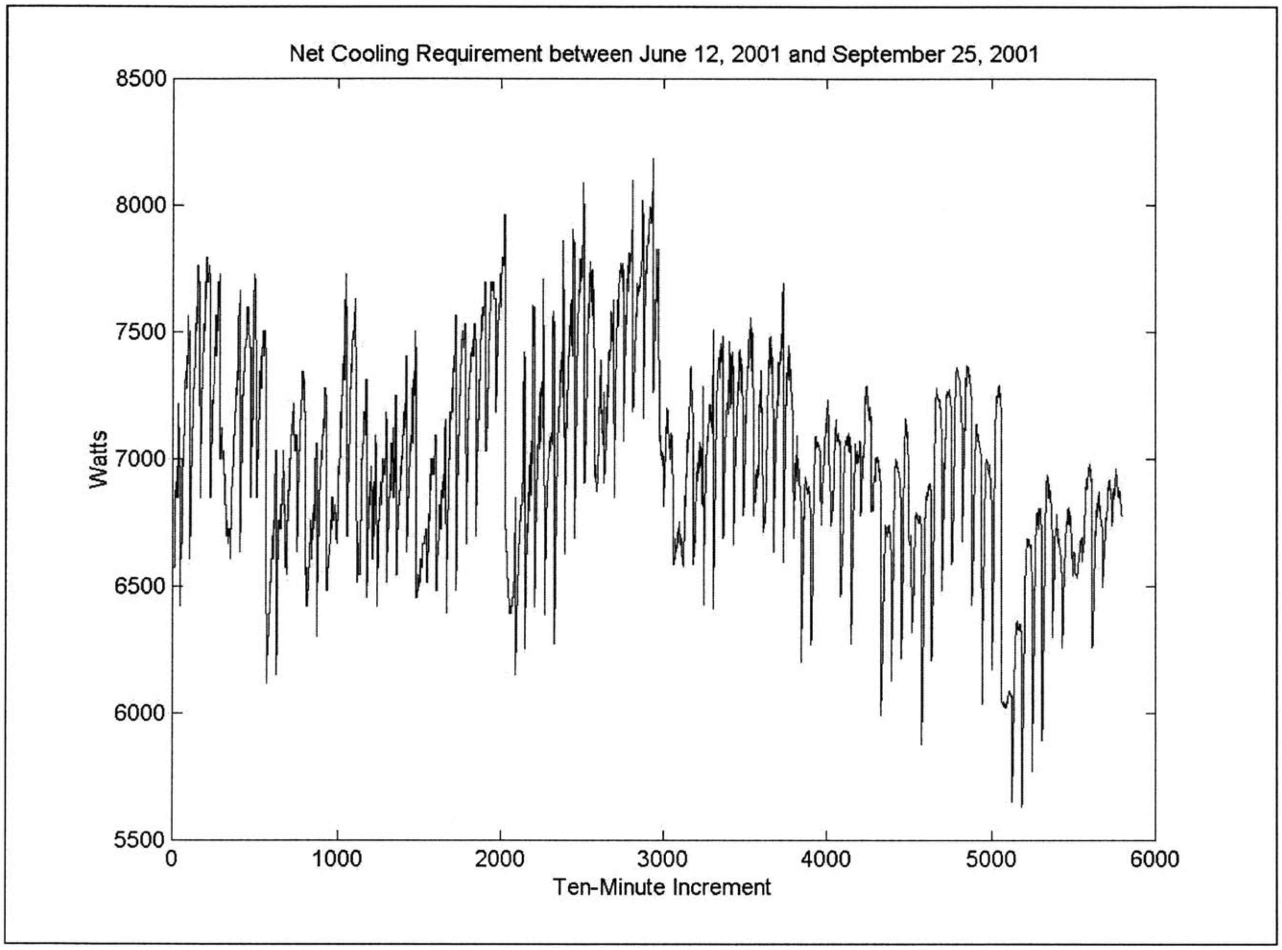


Figure 197 Net cooling requirement between June 12, 2001 and September 27, 2001, during occupied hours.

A highly insulated building structure, coupled with the use of argon-filled, double-glazed windows, leads to a net cooling requirement during the entire natural ventilation period. While the building keeps cold out during the heating season, it also keeps heat in during the cooling season. This makes it imperative that natural ventilation be used 24 hours a day. The net power requirement during the period is 6,760 kW-hr. It should be noted that this calculation is based on average solar and peak internal loads for the entire occupied summer cooling period.

6.2.3 Temperature

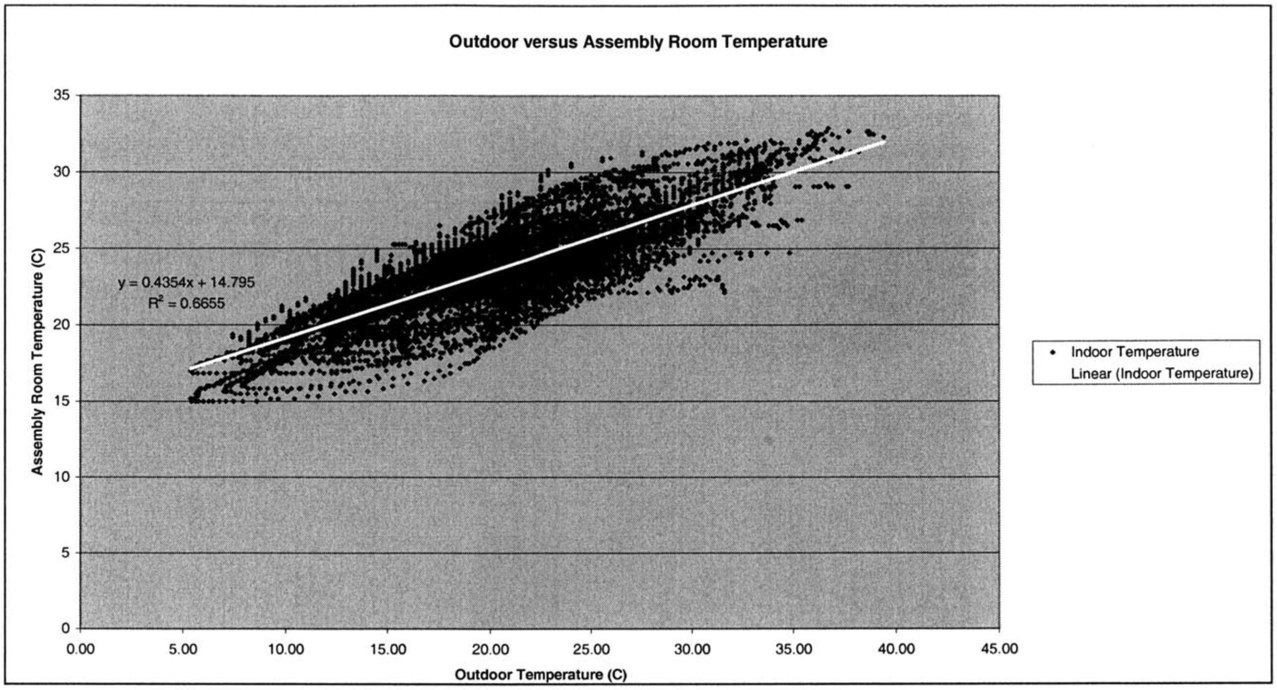


Figure 198 Outdoor versus assembly room temperature with linear trendline.

The above graph shows a plot of all outdoor temperature and assembly room temperature data collected between June 12th and September 25th of 2001. A linear trendline was fitted to the measured average indoor temperature data. It indicates a reasonable correlation between outdoor and indoor temperature, as expected. At 26.2°C, the outdoor trendline temperature equals the indoor trendline temperature. Daytime outdoor temperatures higher than this correspond to a lower indoor temperature, an indication of both the suitability of the space for natural ventilation, and the amount of thermal mass. If there was no thermal mass and ventilation with outdoor air was intensive, we would expect the indoor temperature to be close to the outdoor air temperature. With a significant amount of thermal mass, we would expect the indoor temperature to be lower during the day and lag behind the outdoor temperature, when night cooling is used.

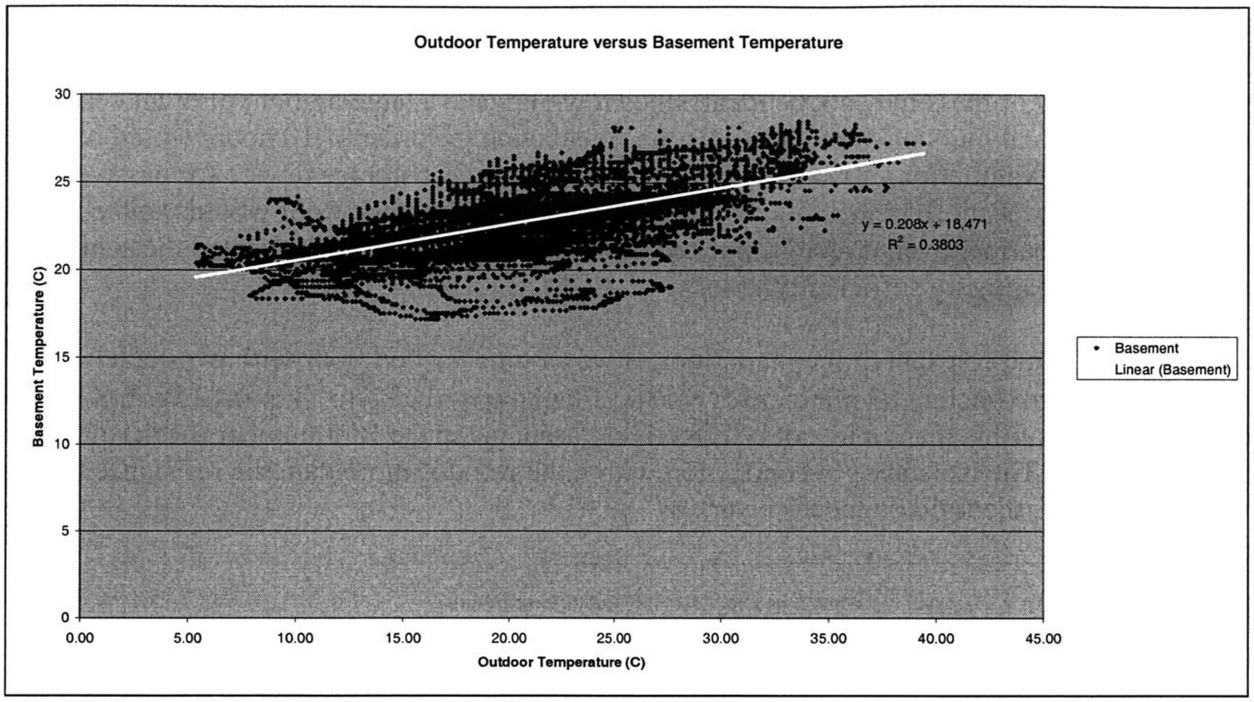


Figure 199 Outdoor versus basement temperature with linear trendline.

The above graph shows a weaker correlation between outdoor temperature and basement temperature than between outdoor temperature and assembly room temperature. This is likely because there is no direct ventilation to the basement. Two things are more likely to effect a change in basement temperature: interior heat sources and the response of the building structure as a whole to external conditions. In some ways, this indicates that direct venting of the basement space during the day may not be desired, in that it would unnecessarily heat up the space and eliminate its use as a comfortable location during extremely hot days. While venting between the first floor and the basement could result in lower first floor temperatures, there is a concern that the basement's thermal mass would heat up too much, since night cooling access to the basement is limited. We see that even at temperatures up to nearly 40°C, the basement stays below 28°C. The high thermal mass of the basement creates a space that changes in temperature very little, even in response to large swings of outdoor temperature. The time constant of the basement mass is almost 24 hours based on the following equation [Incropera & DeWitt, 1996]:

$$\tau = \frac{\rho V c}{h A_s} = \frac{(2050\ \text{kg/m}^3)(80\ \text{m}^3)(960\ \text{J/kg}\cdot\text{K})}{(7\ \text{W/m}^2\cdot\text{K})(260\ \text{m}^2)}$$

where:

ρ = density of brick
V = volume of thermal mass
c = thermal capacitance of brick
h = convection coefficient
A_s = exposed surface area of thermal mass

Such a large time constant makes it hard to correlate environmental conditions, such as the main floor temperature, to the response of the thermal mass. For natural ventilation to be effective, such a large body of mass may not be ideal, since it would take a large amount of night cooling to purge the thermal mass of stored heat. A time constant on the order of 10 hours would be better for natural ventilation. If we look at the basement as a heat storage device for passive solar heating, we would want as high a time constant as possible, so that the floor would radiate heat for a significant period, even if clouds blocked direct solar radiation and prevented the south sunspace from heating up sufficiently.

In contrast, the time constant of the main floor, if we assume a wood floor with two-inch thickness, is approximately 85 minutes ($c_p = 1380$ J/kg·K, $\rho = 510$ kg/m^3, k = 0.12 W/m·K). Even then, most of this mass may not be effectively used, given the Biot number (hL/k) of greater than one. The resistance to conduction within the wood is more than the resistance to convection across the fluid boundary layer.

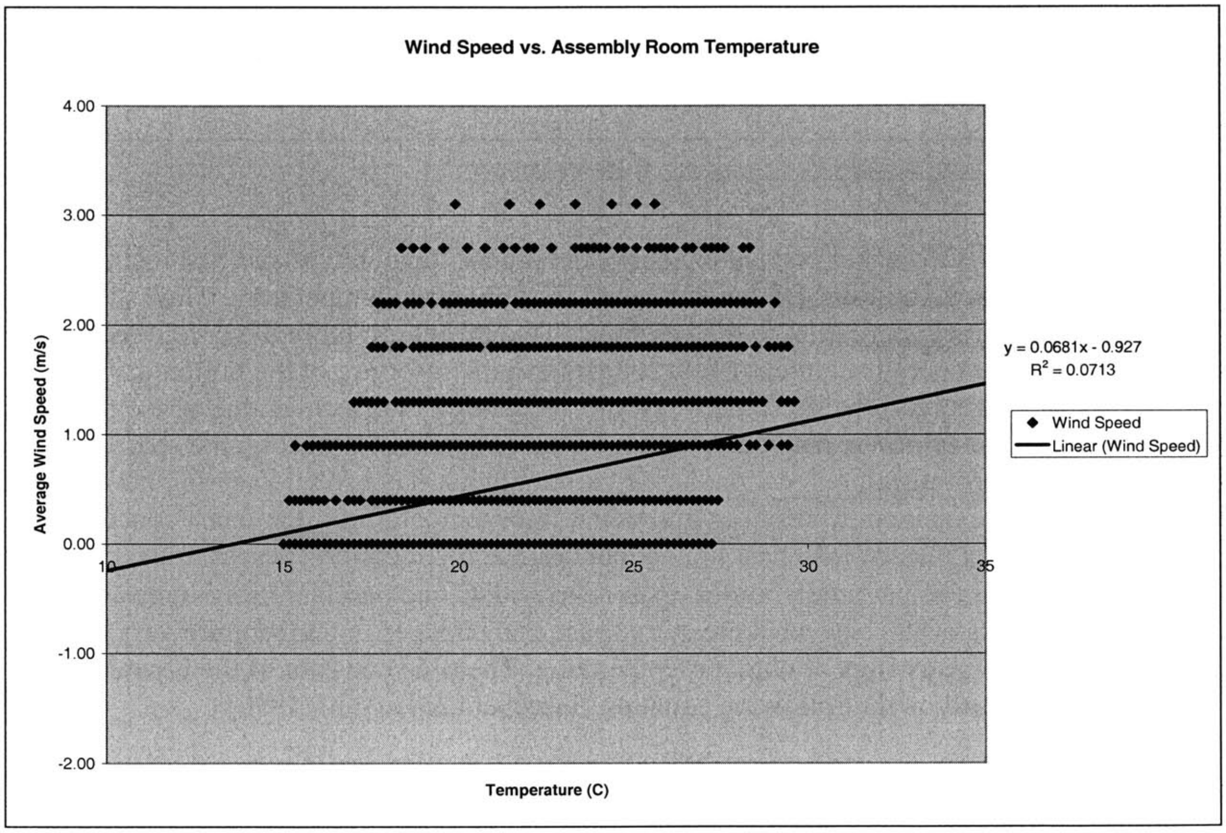


Figure 200 Wind speed versus assembly room temperature.

The above graph is a plot of assembly room temperature versus average wind speed. In this case, there is little to no correlation between the two. The line is a linear trendline fitted to the data. A similar case holds true for wind direction versus indoor temperature.

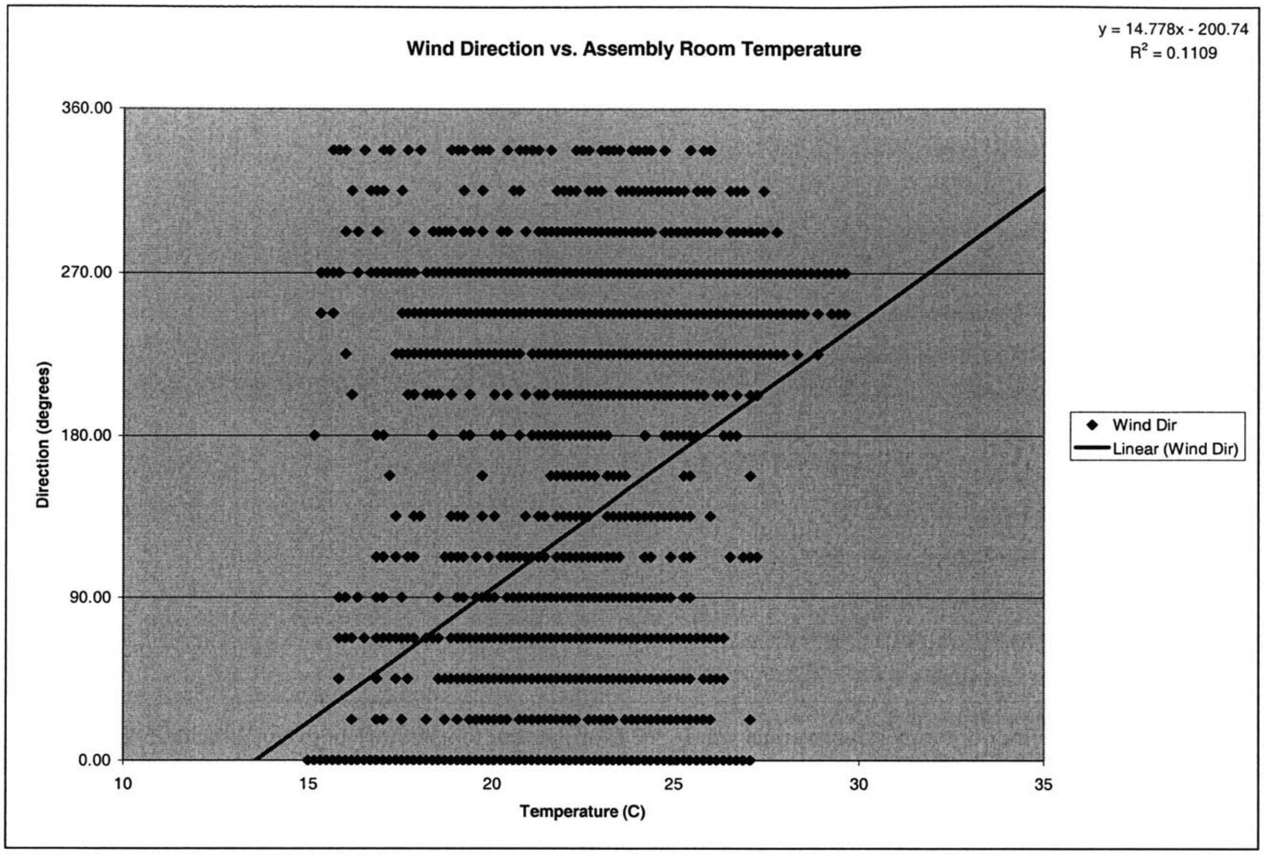


Figure 201 Wind direction versus assembly room temperature.

When a multiple regression is performed with both wind speed and wind direction as independent variables, and the indoor temperature as the dependent variable, the correlation increases only slightly to a coefficient of determination (R^2) value of 0.12. The R^2 value is the percent of the variation that can be explained by the regression equation. The regression equation is *temp* = 21.61783 + 0.389829834 * *wind speed* + .006119043 * *wind direction*. When pondering the thought that favorably directed air at higher velocity would seem to cause lower air temperatures, we note that when there is little wind, or the wind is from a less than optimal direction, the stack effect kicks in and makes up part of the difference. This is because the effective ventilation area from windows and doors is relatively small compared to the overall surface area of the space. We do expect a higher ventilation rate corresponding to higher wind speeds though. Regrettably, this is something that was not measured successfully with tracer gas techniques.

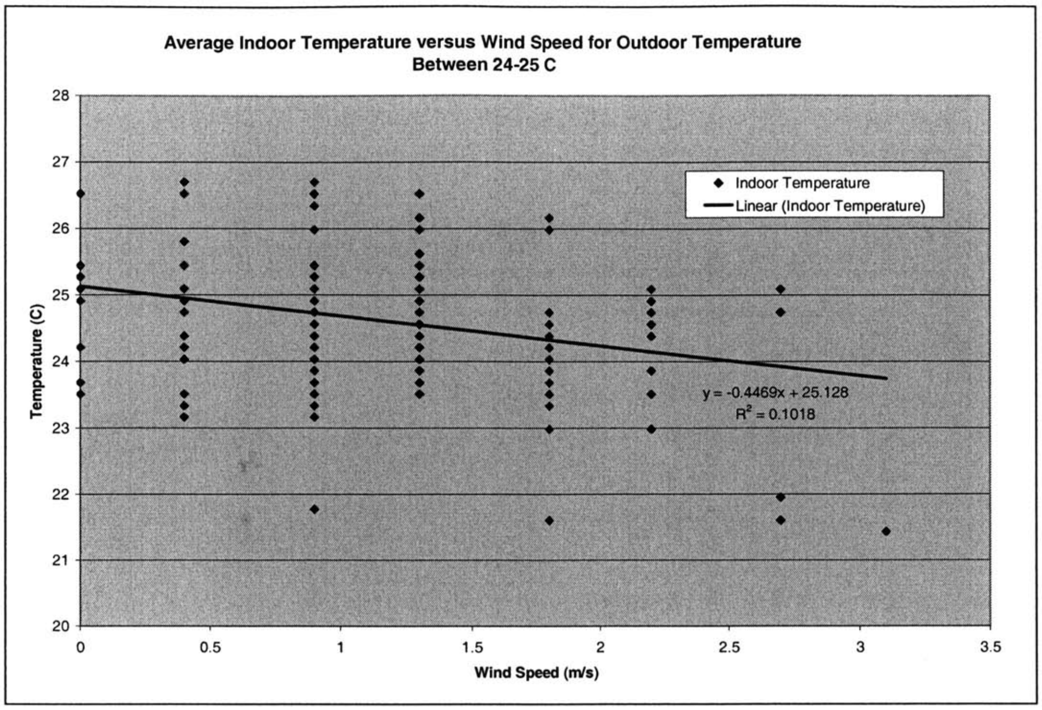


Figure 202 Average indoor temperature versus wind speed for outdoor temperature between 24 and 25°C.

When the wind speed data is isolated by a narrow band of outdoor temperature, there is an increased correlation between wind speed and average indoor temperature. For an outdoor temperature band between 24 and 25°C, we see that there is difference of up to 5°C in indoor temperature, over a difference in wind speed of 3 m/s.

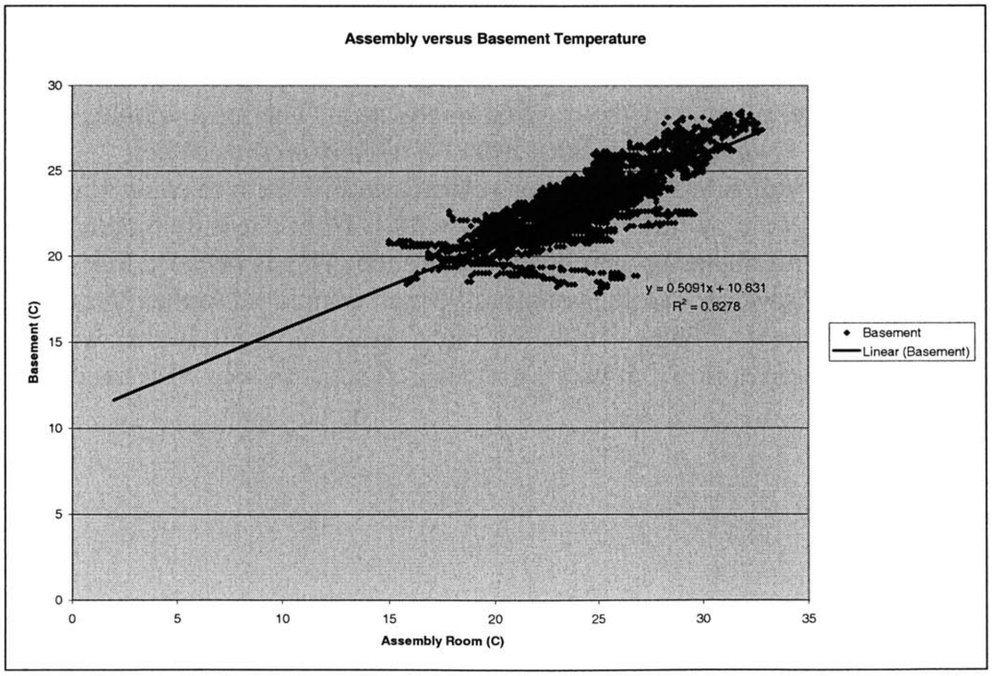


Figure 203 Assembly room versus basement temperature.

A comparison between assembly room temperature and basement temperature indicates a reasonable correlation, with an R^2 value of 0.6278. This appears to initially contradict the notion that the basement is not coupled to outdoor temperature, if the logic that A (outdoors) affects B (assembly room), B affects C (basement), so thus A must affect C, holds true. Further thinking indicates that there may be no contradiction; the basement space is still effectively coupled to the assembly space through transfer vents, a staircase, and lightweight building materials. There is simply not a direct correlation between the outdoor and basement temperatures.

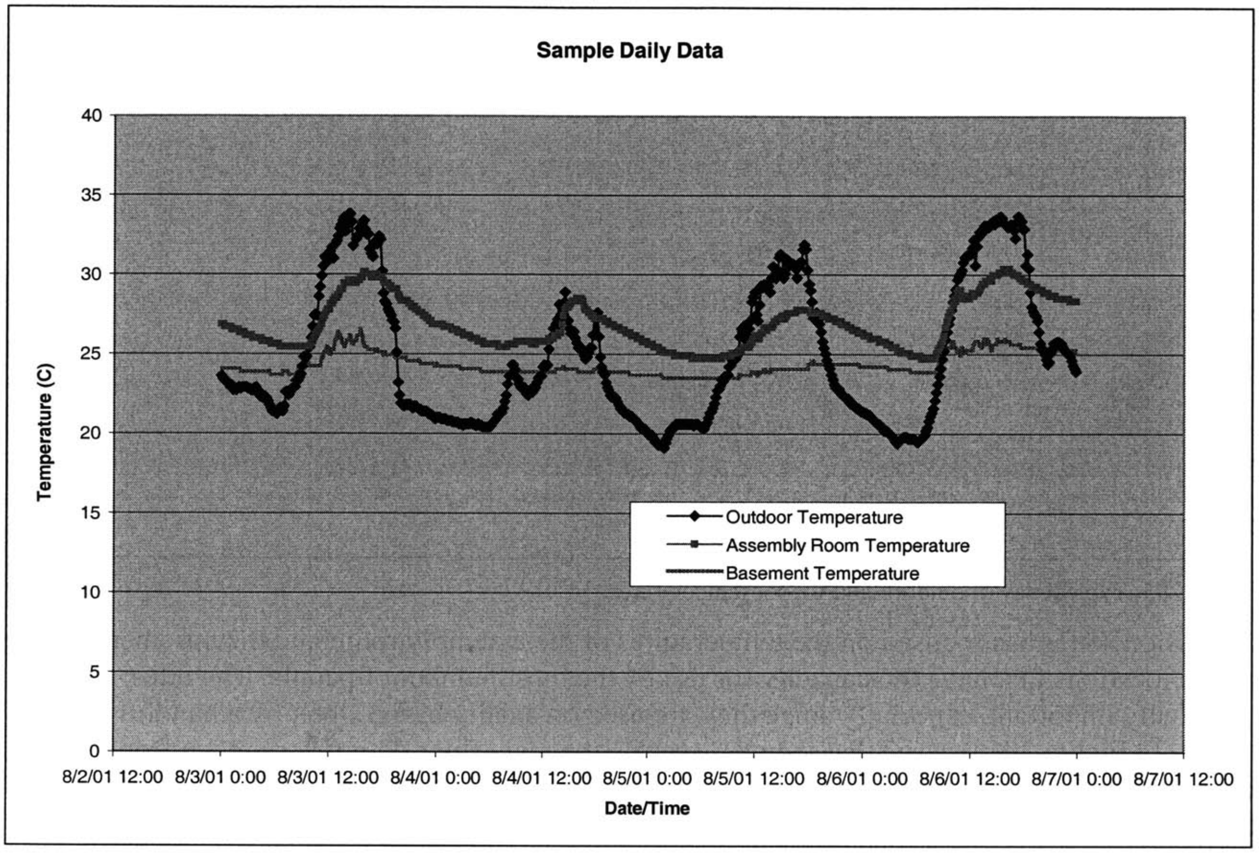


Figure 204 Typical week of outdoor and indoor temperatures.

A sample of data for four of the warmest days in August is shown above. The main floor indoor temperature responds almost instantly to changes in outdoor temperature, an indication that ventilation is high. The basement displays a very flat profile, with also very little lag, an indicator of the massiveness of the material that makes up its floor and walls and the effect of being surrounded on two sides by earth.

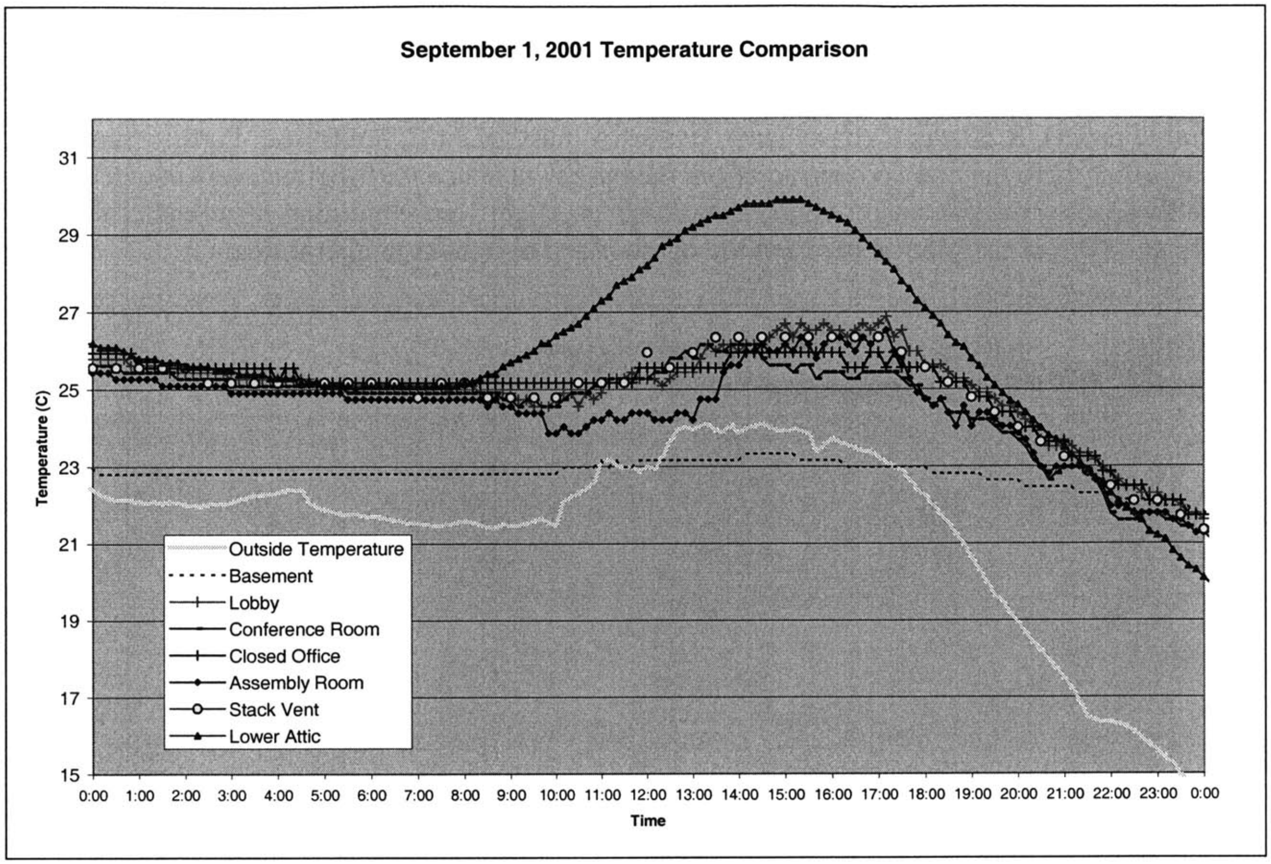


Figure 205 Typical day of outdoor and indoor temperatures.

Discussion so far has focused on the temperatures of the assembly room and the basement. These are the locations that have the capacity for use by the most number of people. The other spaces are equally important, especially since they are used on a daily basis, albeit by a handful of people. In Figure 205, we see that temperatures on the main floor do not vary much from room to room. The attic is at a significantly higher temperature than the rest of the building, indicating that there may be a need for better attic ventilation, to minimize added heat gain through the ceiling of the main floor.

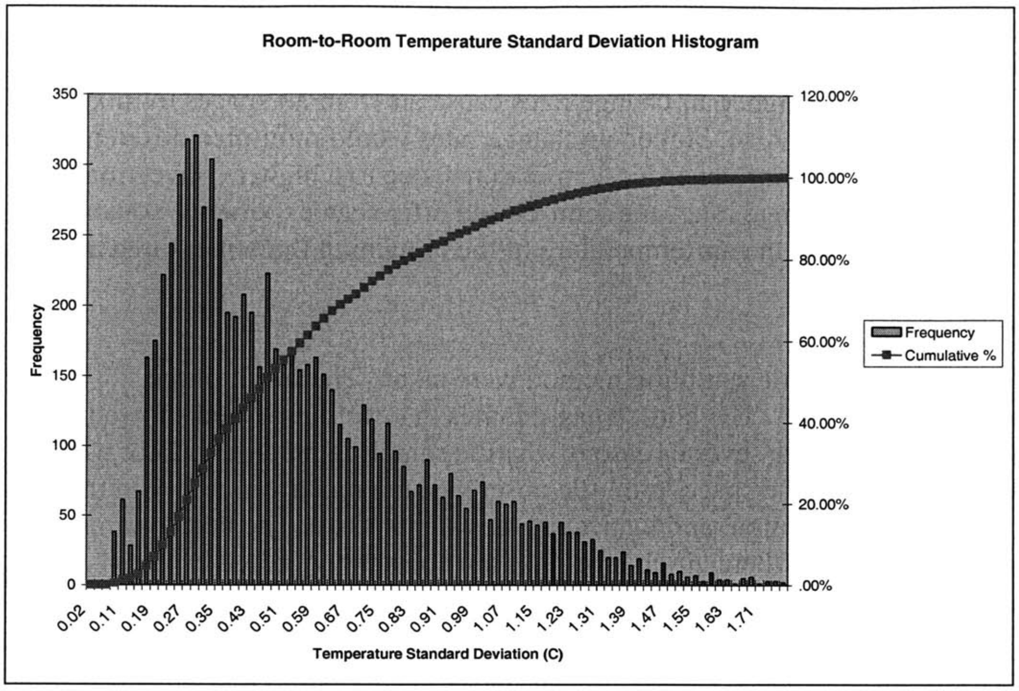


Figure 206 Standard deviation of all measured ground floor zone temperatures (4 locations).

The standard deviation of the temperatures in the conference room, the partially closed office, the lobby/admissions area, and the assembly room, from each other, is typically less than 1.5°C. This is interesting, but perhaps not significant, since the human body cannot significantly detect differences in temperature below 2°C [Chang, 2000]. The most common deviation occurs around 0.27°C, which interestingly enough is the accuracy limit of the HOBO dataloggers.

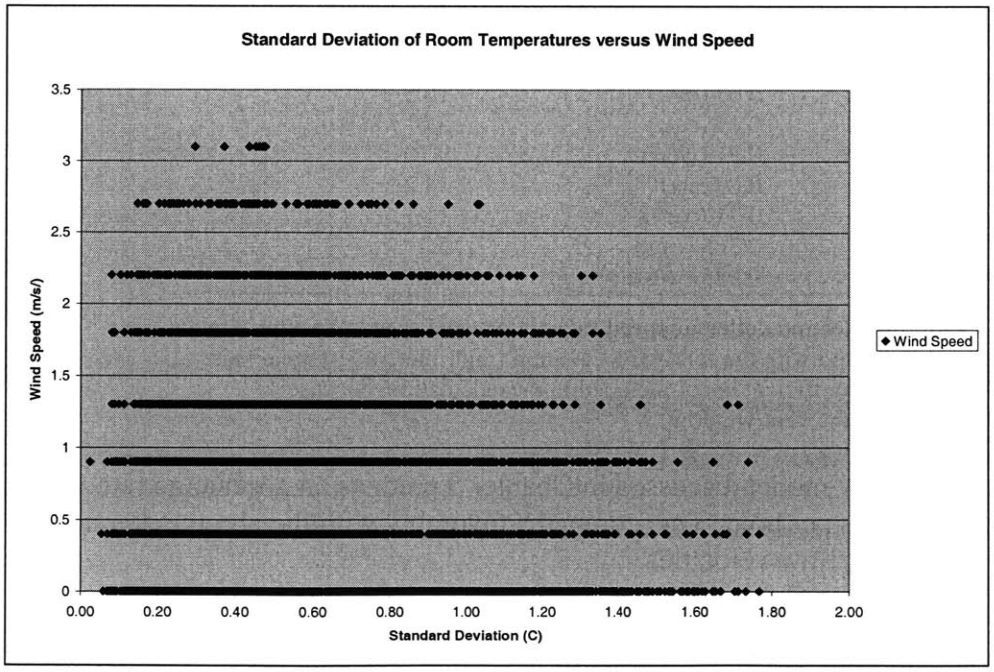


Figure 207 Standard deviation of all ground floor zone temperatures versus outdoor wind speed.

Although the above data is too broad to obtain any linear correlation, there appears to be some bounding. The higher the wind speed, the lower the maximum standard deviation. This would fall in line with the hypothesis that higher air change rates cause air from all spaces to mix more, leading to a more even temperature. Also, higher air change rates would minimize differences in surface temperatures, which directly influence air temperatures, due to a higher convection heat transfer coefficient. At lower air change rates, the semi-closed office can experience some stagnation that brings it farther from the air temperature of the remaining three measured areas.

6.2.4 Air change rates

Measurements using a tracer gas bottle sampling method were taken. The result of the experiments was inconclusive though. The bottled gas samples that were analyzed showed inconsistent concentrations. There are several reasons why the sampling method did not work. They include inadequate mixing in the space, too little doser gas, too much variability in the airflow rate caused by natural ventilation, and inadequate gas sample size. The bottle sampling method was designed for situations where air change rates are constant [ASHRAE, 1997]. It appears that it is difficult to adapt it for a natural ventilation study. The constant concentration or constant supply method should be used instead. They were not used in this study, due complication of transporting and storing fairly expensive doser and analysis equipment.

Airflow measurements with a handheld anemometer were taken on June 30, July 27, August 3, August 16, and September 27 of 2001. A comparison of the measured airflow to the wind speed is provided. A resultant air change rate is also calculated.

Date/Time	Outside Wind Speed	Measured Air Speed	Approximate ACH
8-3/13:45	2.2/SW	1.01 (east)	15.8
8-3/13:47	2.2/SW	0.88 (west)	13.8
8-3/14:23	1.8/SW	0.34 (east)	5.3
8-3/14:24	1.8/SW	1.06 (west)	16.6
8-16/12:24	1.3/NW	1.6 (west)	25
8-16/12:26	1.8/NW	0.67 (east)	10.5
8-16/13:53	1.8/NW	0.19 (east)	3.0
8-16/13:56	1.8/NW	0.91 (west)	9.10
9-27/13:25	1.7/NW	0.8 (east)	14.2
9-27/13:26	2.2/NW	0.71 (west)	11.1
9-27/14:42	2.2/W	0.365 (east)	5.7
9-27/14:43	2.2/W	0.525 (west)	0.82

Table 23 Comparison of measured inlet and outlet air speed to outdoor wind speed. An approximate air change rate per hour is also computed with the following equation (min[inlet,outlet] area * air speed * 3600) / volume. A discharge coefficient is not included in the calculation, because anemometer readings were taken past the vent/window.

For August 16, 2001, the airflow model discussed in Chapter 5 predicts an air change rate ranging from 6 to 10 air changes per hour. This compares favorably with the air change rate calculated from the measured airflow velocities.

Smoke tests using a Drager air current kit were carried out. It showed that air sometimes moved downwards from the attic into the first floor. This is because the cupola on the roof is only open on the west side. When wind comes from the west, air is pushed downwards into the attic. The building, as oriented to predominant winds, is also too deep for the cross ventilation the majority of the time.

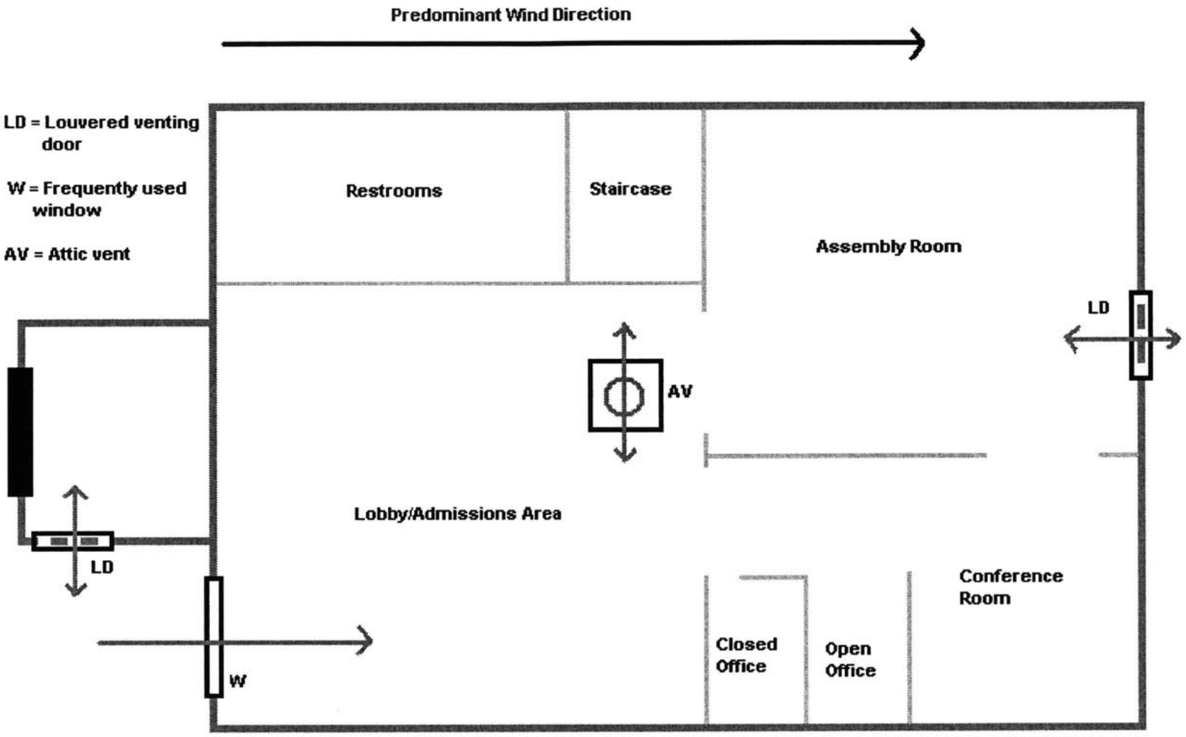


Figure 208 Diagram of visualized airflow using smoke with a westerly wind.

When wind comes from the west, as shown in Figure 208, air is actually pulled outside through the west louvered door, contrary to the original intent of cross ventilation shown in Figure 89. At low wind speeds, the stack effect appears to dominate; air moves *into* the building through both the west and east louvered doors.

6.3 Thermal Comfort

Evaluating how well a building provides thermal comfort, based solely on the comments of its occupants can be difficult, given the subjective nature of responses. On the other hand, using temperature and humidity alone will not show what people are actually feeling. Thus, it is important to combine both measured data with survey data to create an overall picture of thermal comfort.

Based on surveys, it was noted that an ASHRAE thermal sensation value between (-1) and (+1) was considered to be comfortable. In plots below, the Fanger model was calculated using the following parameters, unless otherwise noted: clo = 0.5, M = 100 W/m^2, RH = 50%, $T_{\text{mean radiant}} = T_{\text{air}}$, $V_{\text{air}} = 0.1$ m/s. A clo value of 0.5 corresponds to a clothing ensemble consisting of a short-sleeve shirt and slacks. A metabolic value of 100 W/m^2 corresponds to walking-type activities. Workers at Broadmoor tend to move around more to interact with visitors, than at a more traditional business office.

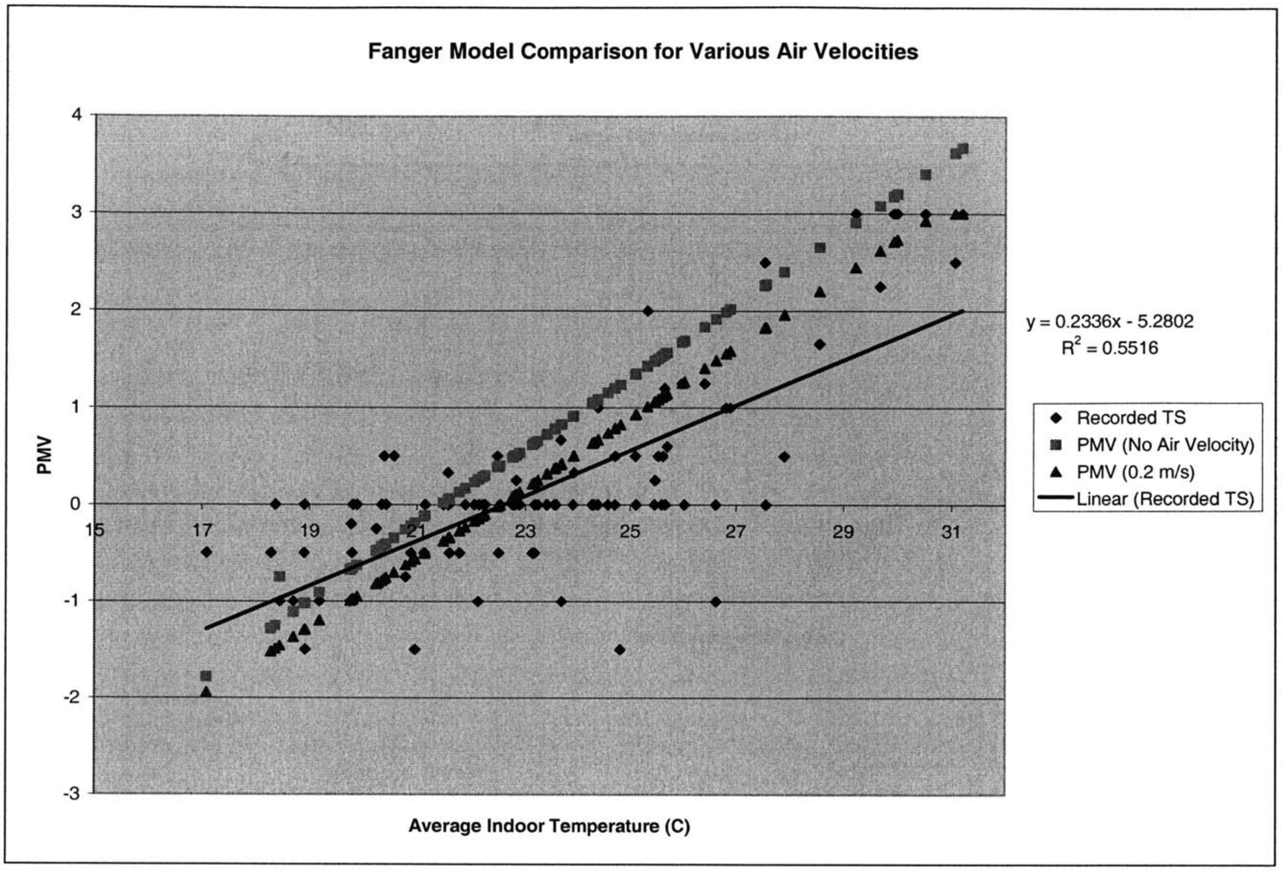


Figure 209 Comparison between Fanger model and surveyed thermal comfort data for various indoor air velocities.

Above is a plot showing the averaged ASHRAE thermal sensation values that were provided by each of the five occupants. The average indoor temperature is based on an average of the occupied-time space temperatures for each day occupants recorded their thermal sensations. A linear trendline shows that there is some correlation between temperature and thermal sensation. What is interesting is what the Fanger model predicts. The occupants experience comfortable conditions at temperatures up to 5°C above those predicted by the Fanger comfort model. The model predicted that people would start to feel too hot—a PMV greater than +1—when the temperature exceeded 25°C. Actual discomfort began to be felt when the temperature exceeded 27°C.

With a velocity of 0.2 m/s, the Fanger model shows the same neutral level as the experimental data, but predicts that occupants will be uncomfortable about 2°C sooner, as the indoor temperature reaches towards 30°C. It is interesting that between 17°C and 26°C, occupants are on a whole comfortable. It is from 28 to 30°C that occupants feel hot.

These results should be taken with a word of caution since the sample size of five people may not be enough for satisfying statistical uncertainty. It is clear that the occupants do feel comfortable at higher temperatures with natural ventilation than predicted by the Fanger model. An increase in air velocity would enhance thermal comfort on particularly hot days.

6.3.1 Detailed Thermal Comfort Questionnaires

A secondary evaluation of thermal comfort can be taken from qualitative surveys that were filled out by all full-time workers in September of 2001. All workers expressed satisfaction with natural ventilation overall. The system works in the building with little need to adjust the building itself. Occupants noted that the building did get very warm during some portions of the summer. Relief was sought by moving to the cooler basement, drinking plenty of fluids, dressing lightly, and using personal desk fans. One worker made an astute comment that it would make more sense to work during the morning, take a midday break, and then work in the evening when it is cooler. Yet, because of cultural standards, this isn't possible. Other workers commented that natural ventilation is feasible at Broadmoor because of a very relaxed dress code. Workers are free to wear puffy goose down jackets when it is cold and sandals and shorts when it is hot.

It appears that a lot of thermal comfort is dependent on psychology. Two workers noted that even during very warm periods, comfort could be maintained by avoiding focus on a particular air temperature. Perhaps this resembles how time goes slowly if you look at your watch every minute, but goes by quickly if you're not wearing a watch at all.

Other significant comments include complaints of odors from the composting toilets. Full-time occupants notice that the high levels of insulation help the building to maintain even temperatures throughout. Natural daylighting was also pointed out as a very beneficial feature. Workers with desks next to the south wall noted that their spaces are sometimes warmer than the rest of the building. This is likely because of excessive heat storage in the trombe wall (water-based) used for passive solar heating. One must remember that the Broadmoor building is located in a region that mainly requires heating. Any trade-offs will be made in favor of the heating season.

Lastly, when occupants were asked if they thought air-conditioning was necessary or even desirable, none replied they would want it. From experience, workers felt that air-conditioning was often too strong, resulting in excessively cool temperatures. Having an abundant amount of fresh air was viewed as paramount to having cool air.

In discussion of thermal comfort, we focus on conditions where occupants feel too warm. This is done because it is easier to warm up—by adding more clothing—than it is to cool down, since the body actively produces heat. With that said, occupants appear to feel comfortable at lower than temperatures than the Fanger model predicts, also.

6.3.1 Outdoor Relative Humidity

One major climate factor that distinguishes the Boston area from Western Europe or the San Francisco Bay Area is the presence of periods of high humidity during the summer. For natural ventilation, this presents a major challenge. Excessive humidity levels prevent people from sweating as easily, thus making them feel more uncomfortable at temperatures they might otherwise feel comfortable at, in climates that are more arid.

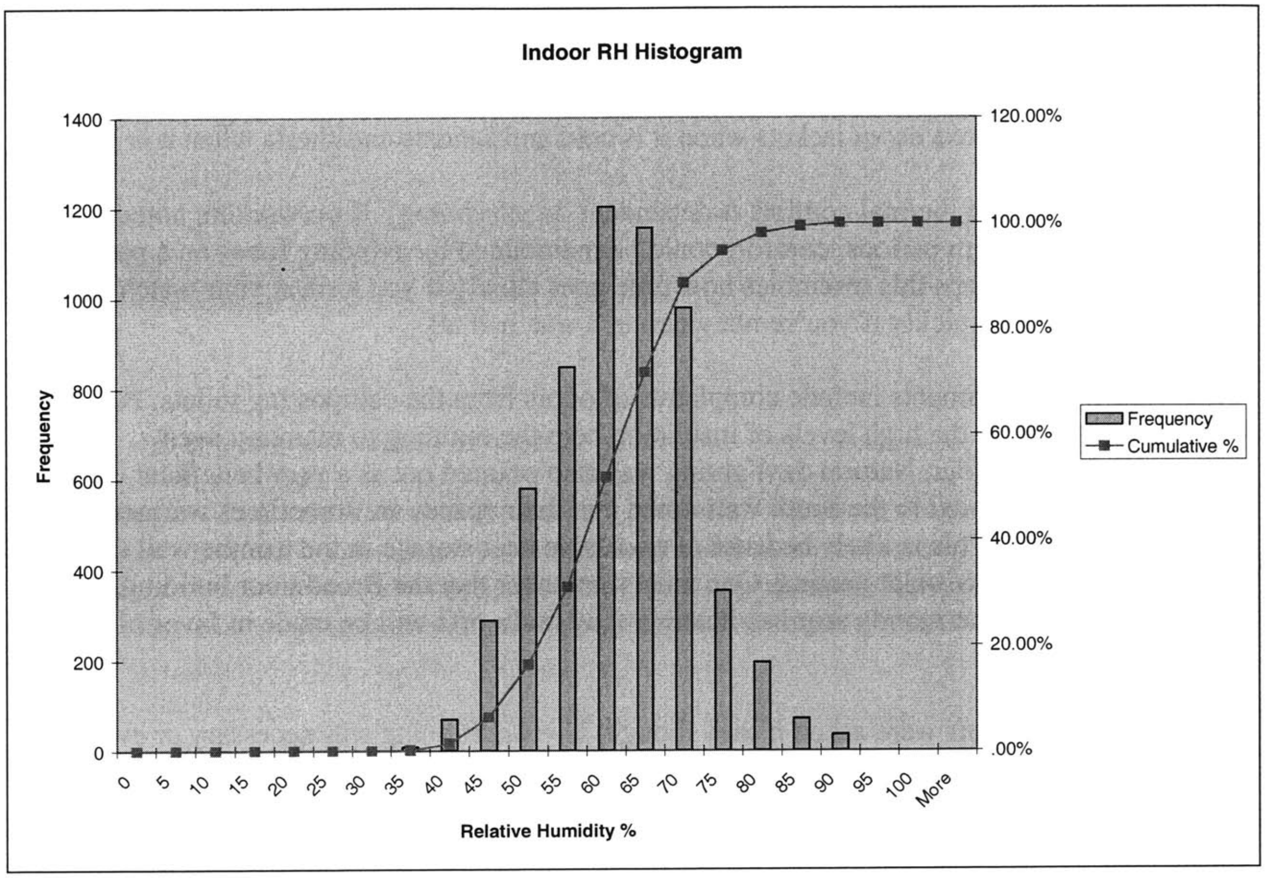


Figure 210 Histogram of indoor relative humidity.

In the above graph, we see that the building experiences higher than desired humidity levels (between 40 and 60% ideal), with a mean around 65%. Further analysis of the data shows that 60% RH is exceeded only 6.6% of the time when the indoor temperature exceeds 27°C, though. Ideally, relative humidity levels should be below 60% for comfort, according to current comfort standards [ASHRAE, 1995].

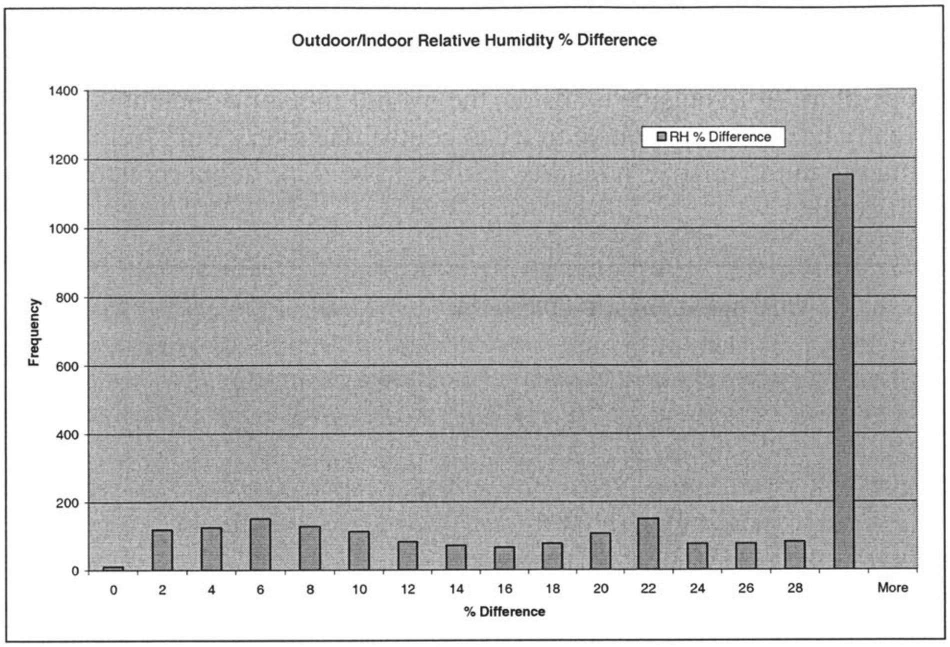


Figure 211 Histogram of percentage difference between outdoor and indoor relative humidity.

We see that the indoor relative humidity exhibits a percentage difference from the outdoor relative humidity over a wide range of values, with the majority of the difference greater than 30%. It appears that the interior space remains drier, with a lower relative humidity, than the outdoors. This is likely due to absorbance of water by the building material, as well as mixing of dry attic air with indoor air. We note that relative humidity is not an absolute indicator of water content and is dependent on temperature. An additional comparison to be performed would be between the outdoor and indoor humidity ratios.

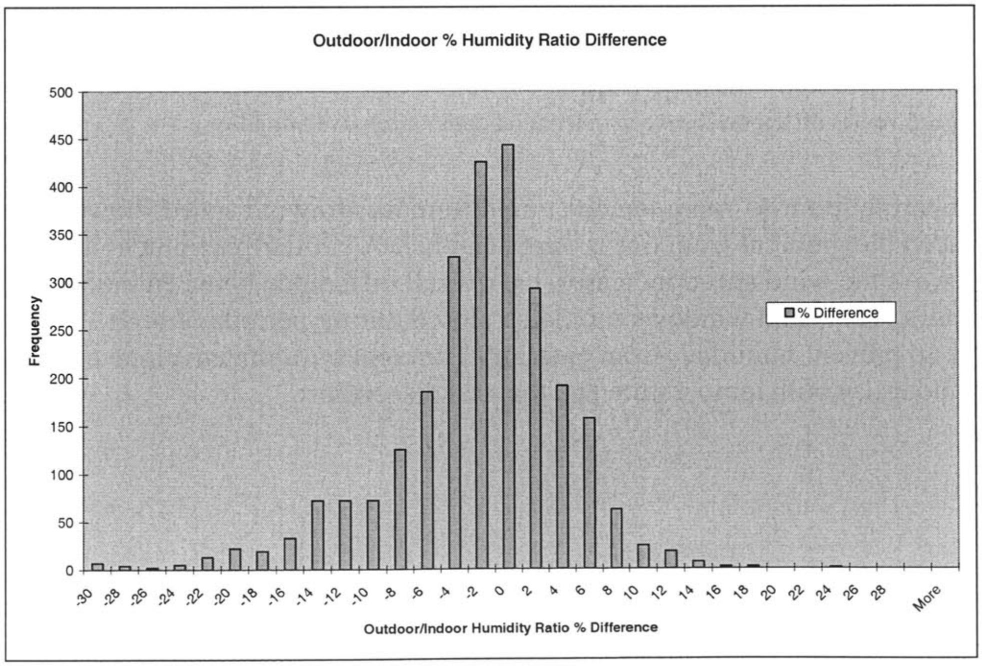


Figure 212 Histogram of percentage difference between outdoor and indoor humidity ratio.

We see that while the outdoor relative humidity was always greater than the indoor relative humidity, the humidity ratio was usually the same, within a band of 10%. So while there may be a difference in dry bulb temperature from outside to inside, the overall moisture content is fairly equal. With that known, it really becomes imperative to try to control the interior dry bulb temperature for comfort, rather than the relative humidity. Little can be done about moisture, without the use of dehumidification.

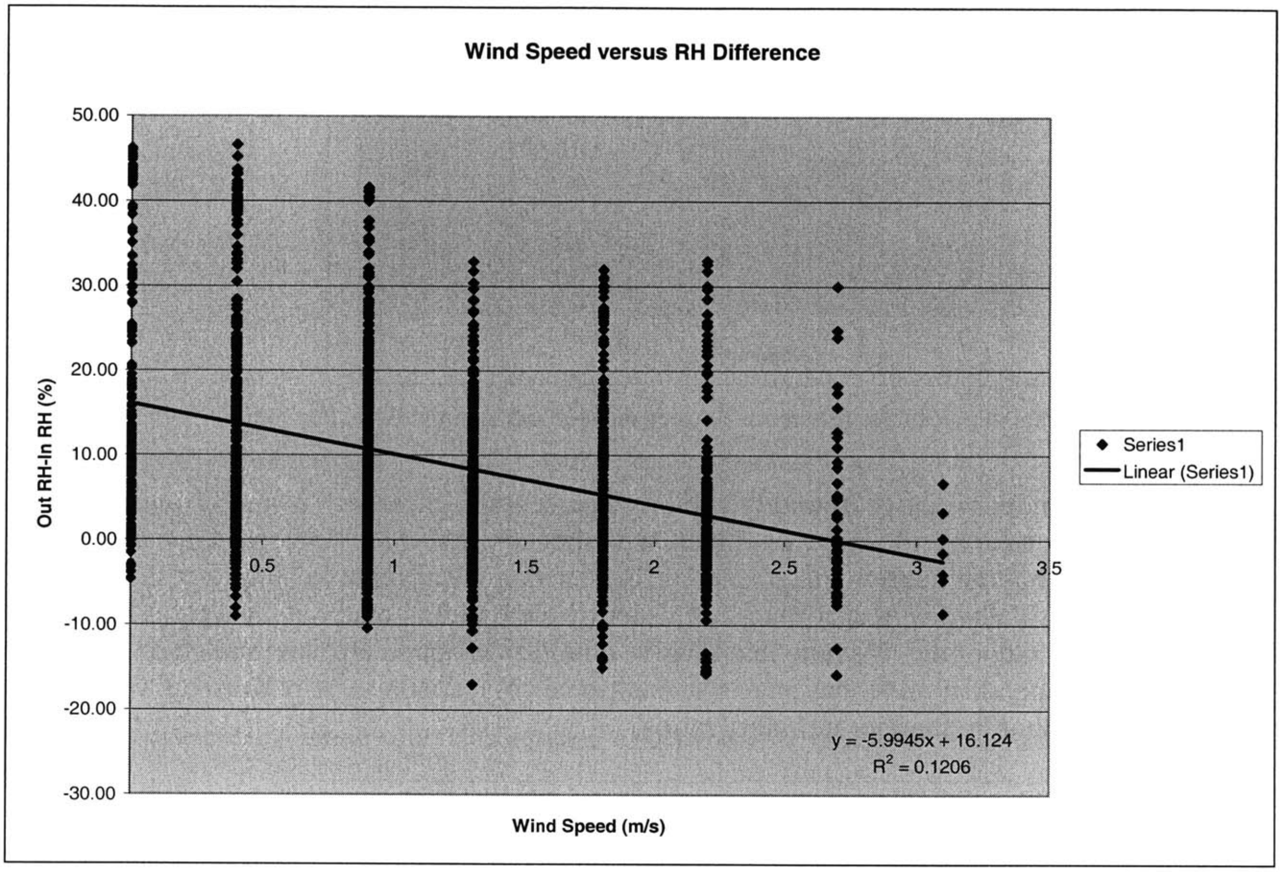


Figure 213 Outdoor wind speed versus difference between indoor and outdoor relative humidity.

A previous exercise comparing room-to-room temperature differences to wind speed showed that higher wind speeds reduced the gradient from one room to another. A similar phenomenon appears in the above plot. As the wind speed increases, the overall difference between indoor and outdoor humidity decreases. Vents and windows should be closed during periods of high humidity *and* high wind, to prevent humid air from entering. The tight building envelope can be used to delay a rise in indoor dry bulb temperature and thermal discomfort.

6.3.2 Indoor Relative Humidity

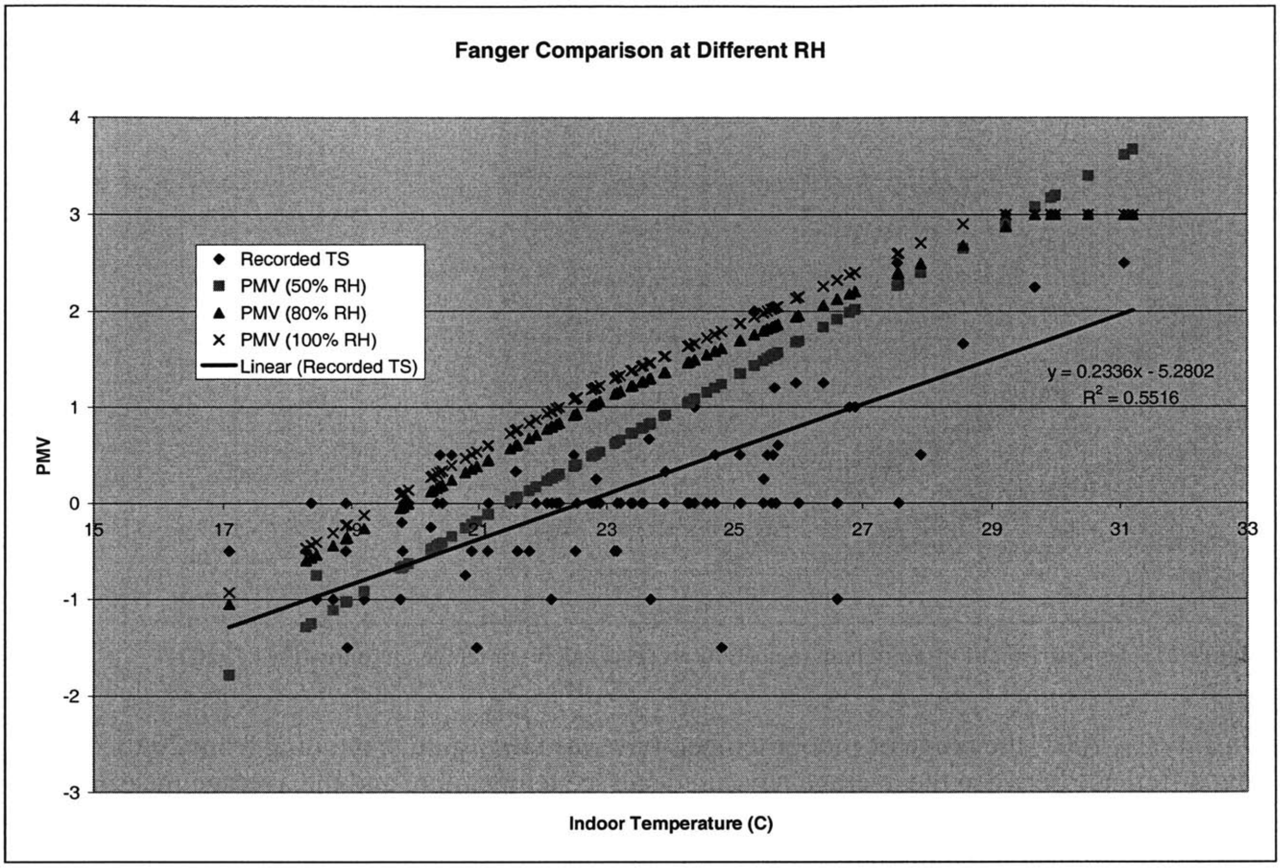


Figure 214 Comparison between Fanger model and surveyed thermal comfort data for various levels of relative humidity.

An increase in relative humidity shifts the Fanger curve upwards, lowering the neutral comfort temperature by another degree. This is another indication of the need to be aware of the outdoor humidity, as a parameter of controlling vents and windows appropriately. A question is how to strike a balance between letting in humid air and closing up a building so long that internal heat loads cause the dry bulb temperature to rise significantly. This is why thermal mass becomes a major necessity. With thermal mass, when temperatures and humidity are high during the day, windows and vents can be shut or minimally open. At night, the windows and vents should be opened to their maximum to cool the mass down.

6.3.3 Mean Radiant Temperature

An often-overlooked thermal comfort parameter is mean radiant temperature. Handheld surface temperature measurements were taken during each site visit. A sampling of results will be presented.

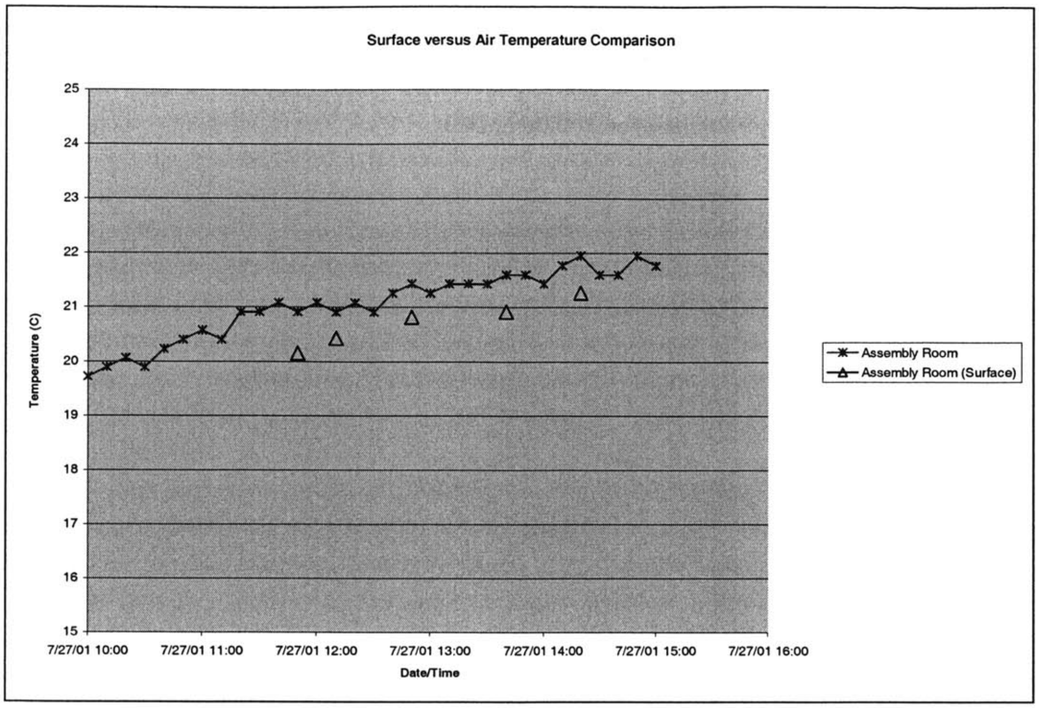


Figure 215 Comparison of mean radiant temperature versus indoor air temperature for July 27, 2001.

On July 27, 2001, the range of indoor temperature was fairly mild, extending from 20 to 22°C. The difference between the average measured surface temperature and the average measured air temperature was less than 1°C. Wind speeds on this particular day were typically at around 1.2 m/s, averaged over ten minute intervals.

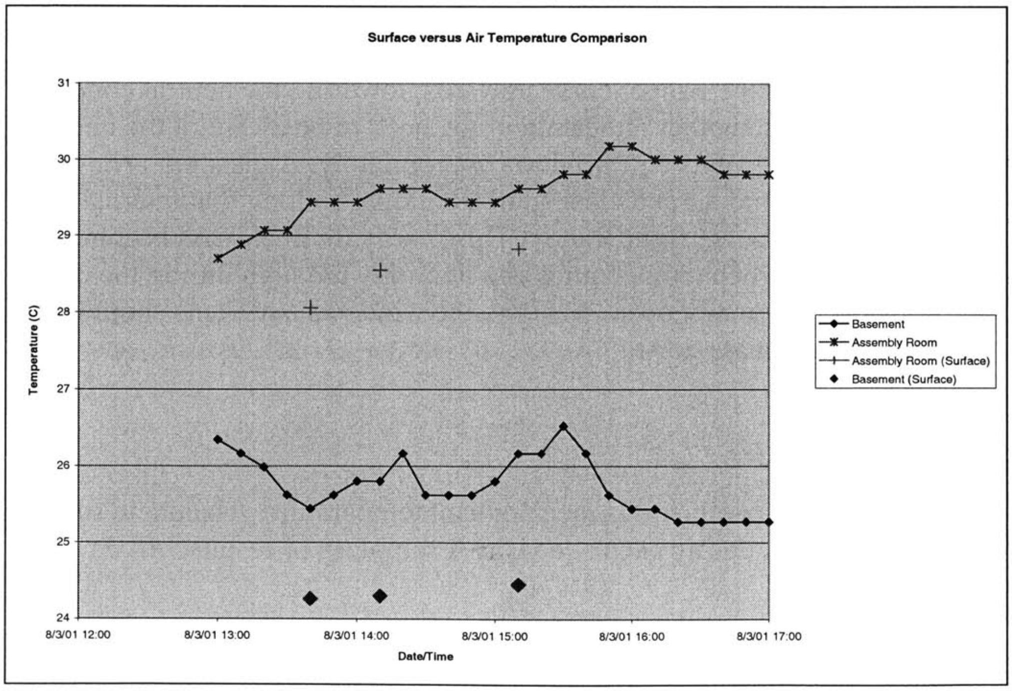


Figure 216 Comparison of mean radiant temperature versus indoor air temperature for August 3, 2001.

On August 3, 2001, the range of indoor temperatures was among the highest for the summer, extending up to 30°C in the late afternoon. The difference between measured averaged surface temperature and air temperature was between 0.5 and 1.5°C. Wind speeds picked up over the day to be higher than typical, at up to 2.2 m/s from the west, averaged over ten minute intervals. This would explain the closing gap in surface and air temperature as the day moved on. The basement surface temperature remained approximately 1°C lower than the air temperature, most likely because of the high availability of thermal mass.

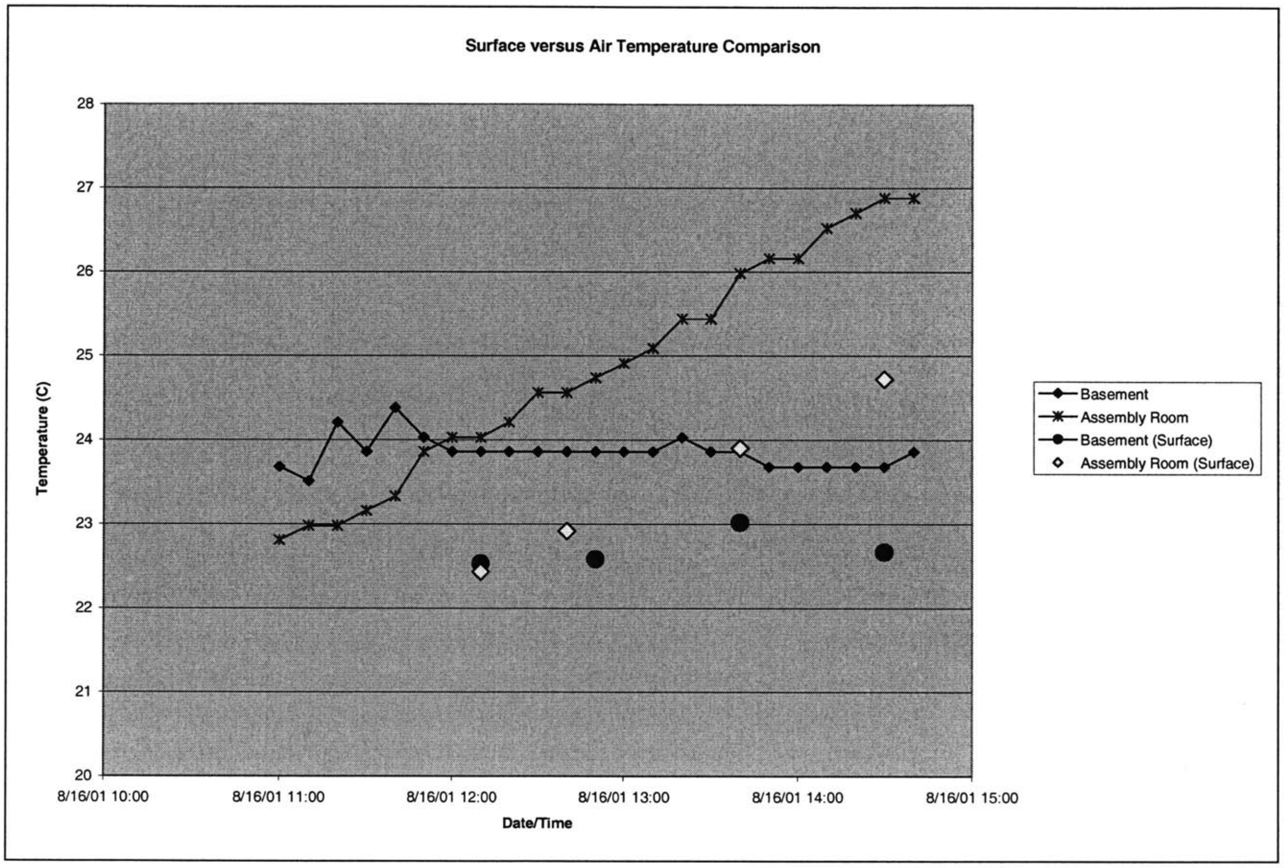


Figure 217 Comparison of mean radiant temperature versus indoor air temperature for August 16, 2001.

On August 16, 2001, the outdoor temperature rose more rapidly than usual. Coupled with higher than typical wind speeds of up to 2.2 m/s from the west, the building's mass appeared to respond at the same rate as the corresponding indoor air temperature, although it typically remained between 1.5 and 2°C lower than the air temperature. The basement exhibited a very flat temperature response with differences in air and surface temperature of less than 1°C. Once again we see the effect of thermal mass. The walls and floor of the assembly room are light in density, while the basement walls and floor are extremely massive.

On several other days, one-time measurements of surface temperature were taken. On June 12, 2001 at 12:50 pm, the averaged surface temperature was 22.1°C, while the air temperature was at 22.3°C, a difference of 0.2°C. On June 30, 2001 at 4:00 pm, the surface temperature was 28.6°C, while the air was at 30°C, a difference of 1.4°C. On August 24, 2001 at 2:40 pm, the surface temperature was 24.2°C, while the air temperature was 26.9°C, a difference of 2.7°C. On this day, wind speeds were lower than normal at 0.9 m/s from the northeast, over ten minute intervals.

The general conclusion is that during the day, at least, surface temperatures are typically between 0.5°C and 2.5°C lower than air temperatures, depending on the amount of ventilation in the space. The following plot shows the resultant effect on the Fanger model.

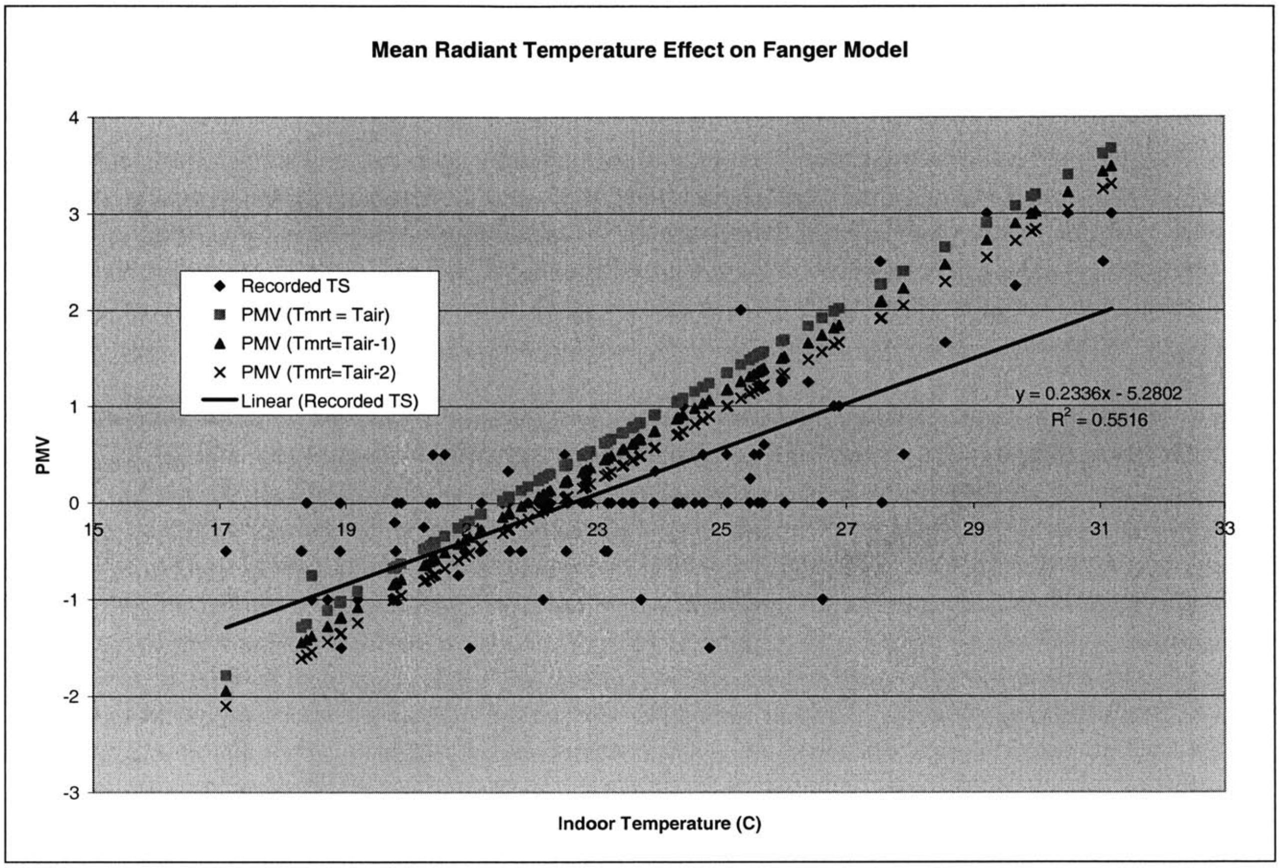


Figure 218 Comparison of Fanger model with surveyed thermal comfort data for various mean radiant temperatures.

A mean radiant temperature of 2°C less than the air temperature results in a Fanger model shift to the right of approximately 1°C. This moves the neutral temperature point to coincide with the average neutral point indicated by occupants in their surveys. The Fanger model still exhibits the same slope though. In general, occupants still indicate more comfort at higher temperatures than the empirical model predicts.

6.3.4 Other Thermal Comfort Parameters

Other important measures of thermal comfort include: asymmetric thermal radiation, vertical air temperature differences, warm or cold floors, and draft. An analysis of predicted percentage dissatisfied is provided in the following table:

	Asymmetric Thermal Radiation	Vertical Air Temperature Difference	Warm or Cold Floors
June 12	<1%	<1%	8% cold
June 30	1.5%	1.5%	10% warm
July 27	<1%	<1%	10% cold
August 3	<1%	<1%	10% warm
August 24	<1%	<1%	7% cold
September 11	<1%	<1%	6% cold
September 27	<1%	<1%	15% cold

Table 24 Evaluation of asymmetric thermal radiation, vertical air temperature difference, and warm or cold floors, for thermal comfort.

It appears that the building enjoys a very even temperature throughout. The high levels of insulation in the building are likely the reason for this. High air change rates induced by natural ventilation can also even out the temperature in the space, as long as there is flow to all parts of the building.

6.3.5 Thermal Comfort Discussion

Although the amount of thermal comfort data collected for this building is minimal, it still reveals that occupants feel comfortable, even at temperatures higher than 27°C. There are many explanations as to why this has occurred; most of the explanations point to a concept of adaptation. Occupants are able to adjust their working style to fit their environment.

Recent research by Fanger and Toftum (2002) indicates that while the PMV model agrees with high-quality studies in buildings with air-conditioning, the PMV model under predicts the temperatures occupants in naturally ventilated buildings are willing to tolerate. They explain this as being caused by lower expectations, as well as metabolic rates that are estimated too high under warm conditions. They have created an extended PMV model that uses an expectancy factor that adjusts according to expectations and activity level.

We see in Figure 219 that the extended PMV model now over predicts the temperatures that occupants will feel comfortable at. On the hottest days, occupants have said that the air in the space gets stagnant, due to very little air movement. It should be noted that the extended PMV model assumes an air velocity of 0.3 m/s, which is higher than any values measured in the interior space.

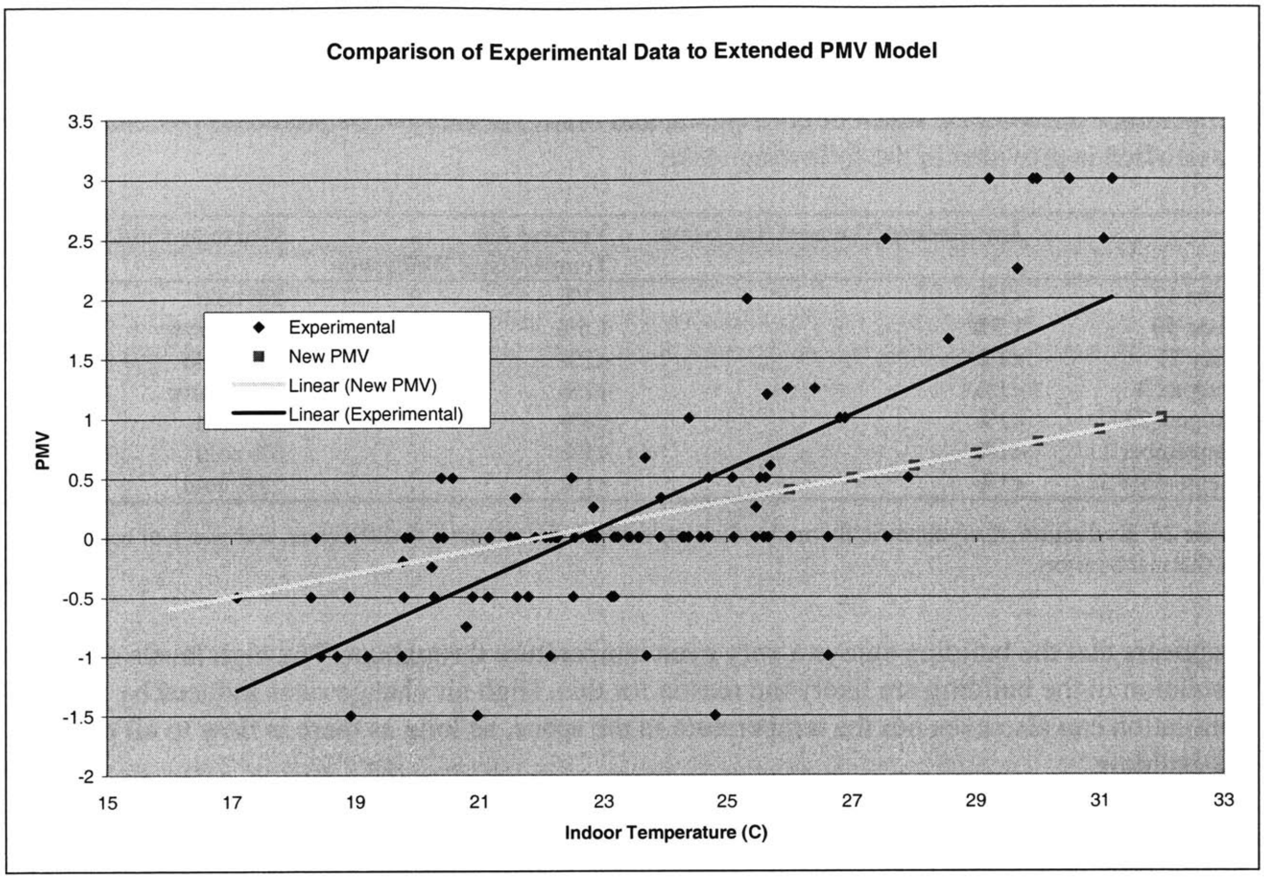


Figure 219 Comparison of experimental data with extended PMV model.

In an upcoming revision to ASHRAE Standard 55, an optimum comfort temperature corresponding to a particular outdoor temperature has been defined as, $T_{comf} = 0.31T_{a,out} + 17.8$ [Brager & de Dear, 2002]. An acceptability range corresponding to this comfort temperature has been defined. An analysis of Broadmoor data according to this range is shown in the following table:

Difference between indoor temperature and optimum comfort temperature	Hours	Percentage
>3°C	20.3	2.1%
$2 < T_{diff} \leq 3$°C (80% satisfied)	42.5	4.4%
$0 \leq T_{diff} \leq 2$°C (90% satisfied)	222.7	23%

Table 25 Analysis of optimum comfort temperatures for Broadmoor occupied hours between June 12, 2001 and September 25, 2001.

We see that conditions were suitable for natural ventilation for the majority of the time (~98%). On the four days when occupants rated a thermal sensation of +2 ("warm") or higher, the indoor temperature either exceeded or came close to exceeding the optimum comfort range under a 90% satisfaction criterion. This analysis focused only on times when the indoor temperature *exceeded* the comfort temperature. It appears that the revised ASHRAE 55 standard makes natural ventilation much more feasible.

6.4 Thermal Model

The model developed for use in this project is fairly basic. It is not expected that it would provide pinpoint accurate results; only a ballpark estimate of indoor air temperatures with time is expected. The difficulty in validating a single-zone model is that there are inputs to the model that were not measured for practical reasons or were measured, but without much success. Among these inputs is solar radiation and overall building air change rate.

Currently, a standard model described by ASHRAE predicts solar radiation. This model is purely based on a clear sky condition. Given that two-thirds of the days in each month are cloudy or partly cloudy, this presents a complication. In later discussion, we will see that solar gains are significant in comparison to internal heat gains. There is no external shading for the building, while internal shading is rarely used.

6.4.1 Internal Loads

Heat Source	Continuous Heat Load	Quantity	Total Heat Load	Night Use
People	132 W	5	660 W	No
Computer Monitor	70	4	280	No
Computer	75/30 (standby)	4	300	Yes
Laser Printer	215/35 (standby)	1	215	No
Fax Machine	30/15 (standby)	1	30	No
Desk Copier	400/20 (standby)	1	400	No
All Lighting	Assorted	82	4,200	Yes
Typical Lighting	Assorted	14	640	Yes
Art Display Lighting	Assorted	50	2,800	Yes

Table 26 Summary of internal heat loads [Wilkins & Hosni, 2000].

The lighting was broken down into three categories. For 'All Lighting', this is the heat load if every single light available on the main floor were turned on. The only time this would occur is at night during lectures. During the day, when natural daylight is available, the center staff is conscientious about using minimal lighting. They will typically use a maximum of four desk lamps with 60-watt incandescent bulbs and turn on a row of indirect fluorescent lamps (ten 40-watt tubes). The total peak load during the day runs around 2,525 watts. Some lighting, computers, and equipment are left on during the night. This runs at 190 watts for equipment and up to 200 watts for lighting. Night heat levels were set at 600 watts. The art display lighting in the assembly room is typically turned on during the weekends.

A complication with heat loads is that there is a convective and radiation split to the instantaneous heat transfer. In order to make the model easy to use, we simply assume that 100% contributes convectively. A better alternative, albeit a more tedious one, would be to use the radiant time series method. This method dictates over a 24-hour period which fraction of radiative gain is converted to a convective gain over each hour in that period. For example, a computer that is turned on at 9 am for an hour may not have all its heat gain converted to direct heat gain until the afternoon, depending on the characteristics of the building materials that will be absorbing heat by radiation. Since the main level of Broadmoor features a light to medium thermal mass with uncarpeted floors, we reach 90% conversion by the sixth to twelfth hour.

Assuming instantaneous conversion may not be an ideal assumption, but it is a sufficient one for simplicity.

Heat source	**Radiative**	**Convective**
Wall, window conduction	63%	37%
Roof conduction	84	16
People	70	30
Lighting	67	33
Equipment	20	80
Transmitted solar heat gain	100	0
Absorbed solar heat gain	63	37
Infiltration (natural ventilation)	0	100

Table 27 Summary of convective and radiative split for heat loads [McQuiston et al., 2001].

Hour	**Light**	**Medium**	Hour	Light	Medium
0	41%	31%	12	1	1
1	20	17	13	0	1
2	12	11	14	0	1
3	8	8	15	0	1
4	5	6	16	0	1
5	4	4	17	0	1
6	3	4	18	0	1
7	2	3	19	0	0
8	1	3	20	0	0
9	1	2	21	0	0
10	1	2	22	0	0
11	1	2	23	0	0

Table 28 Summary of radiant time series percentages for light and medium construction buildings [ASHRAE, 2001a].

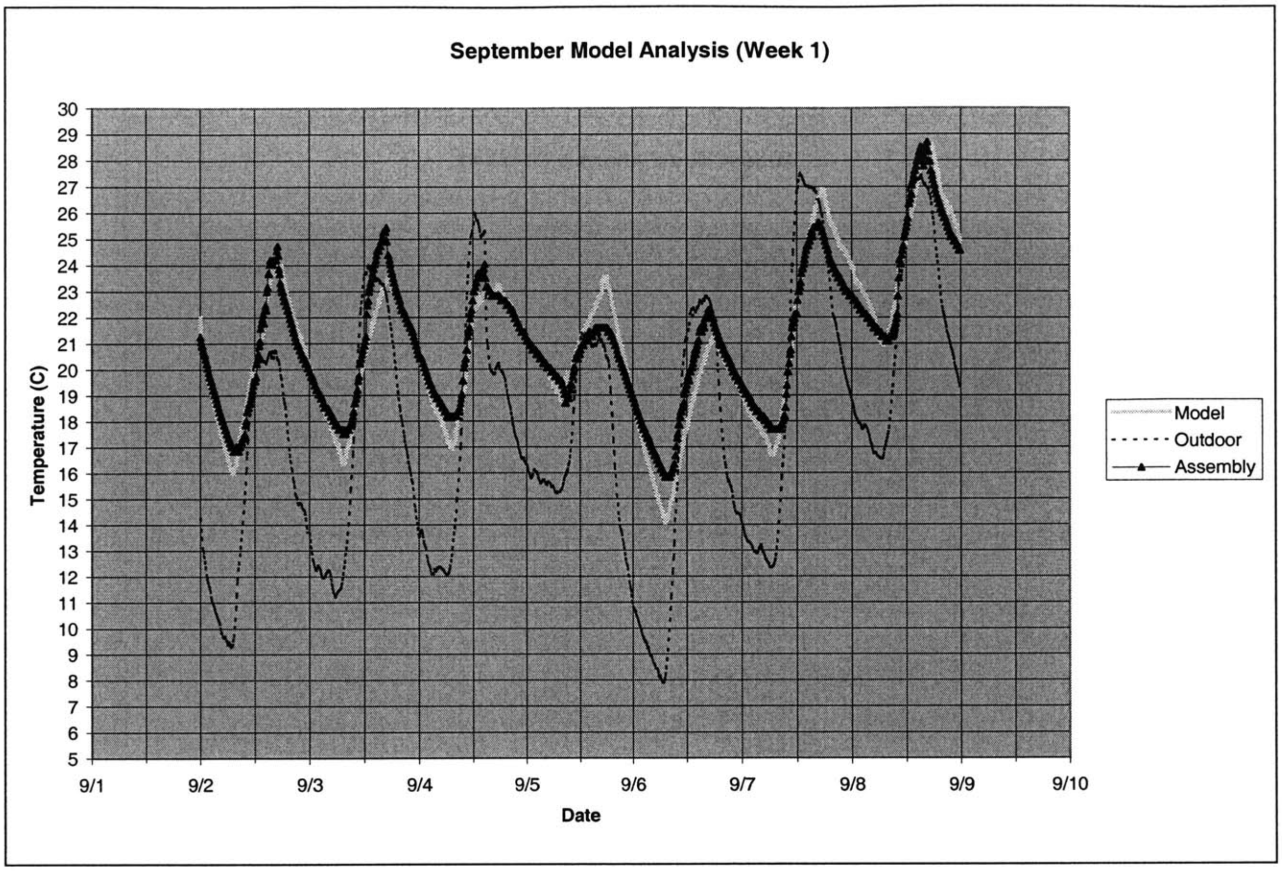


Figure 220 Comparison of model predication with actual temperature data for the first week of September 2001.

The results of the model are shown for an entire week in September. The model performs surprisingly well, even with a mix of different outdoor air temperatures. The model appears to track the peaks and valleys, as well as the slope of temperature change well. The error between measured values and the model never exceeds 10%.

A further breakdown of the results shows the largest discrepancies occurred on September 3 and September 5. The most likely cause of error on September 3 is the translation of actual cloud cover data from Boston Logan International Airport. Data from Logan Airport is provided in the following sample format: FEW018, SCT070, OVC180. The three numbers indicate the height in hundreds of feet. CLR = clear, FEW = 0/8-2/8 cloud cover, SCT = 3/8-4/8 scattered cloud cover, BKN = 5/8-7/8 broken cloud cover, OVC = 8/8 overcast. For the model, the following scaling factor was used to correspond to the most dense cloud layer: CLR = 100%, FEW = 75%, SCT = 50%, OVC = 25%. A more detailed evaluation of methods for generating solar radiation data based on cloud cover and sunshine models is provided by Muneer and Gul (2000). Those methods are much more involved and require that data be in a very specific format.

On September 5, the main condition that was different was a predominantly northwest wind. On the other days discussed, wind primarily came from the west. It is possible that the British Standard Method airflow model was not able to accurately account for wind from the northeast, because the northeast corner of the building is fairly close to trees that could enhance flow through the building. We note that the actual room temperature on September 5 was very close to the outdoor temperature.

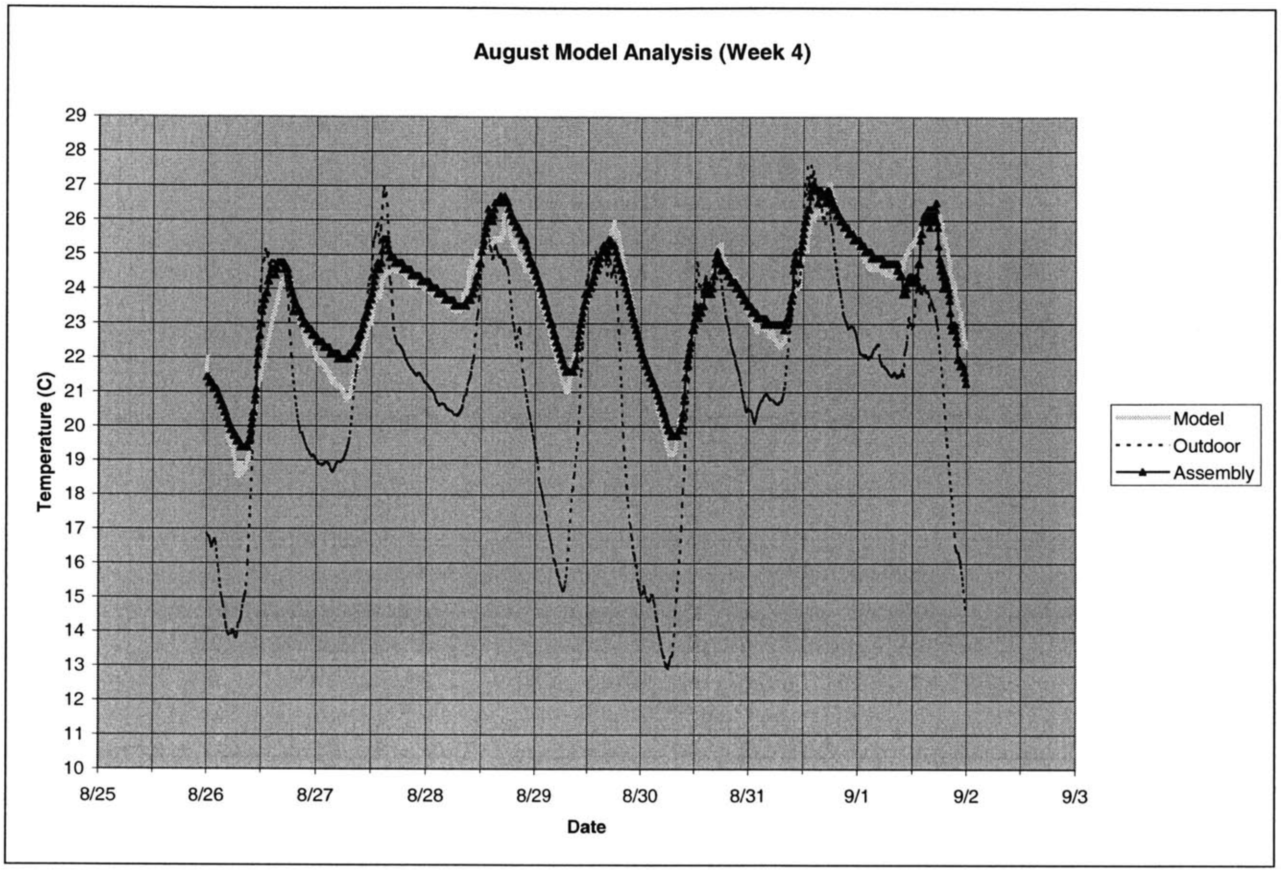


Figure 221 Comparison of model predication to actual temperature data for the fourth week of August 2001.

Upon inspection of data from the last week in August, we see once again that the model works extremely well. In this case, the error never exceeds 5%. The only item that varies in the model input is the amount of cloud cover. A standard internal heat load schedule was used, along with window and door operation data noted by occupants. The outdoor temperature exhibited a different profile each evening, a strong test of the model's abilities.

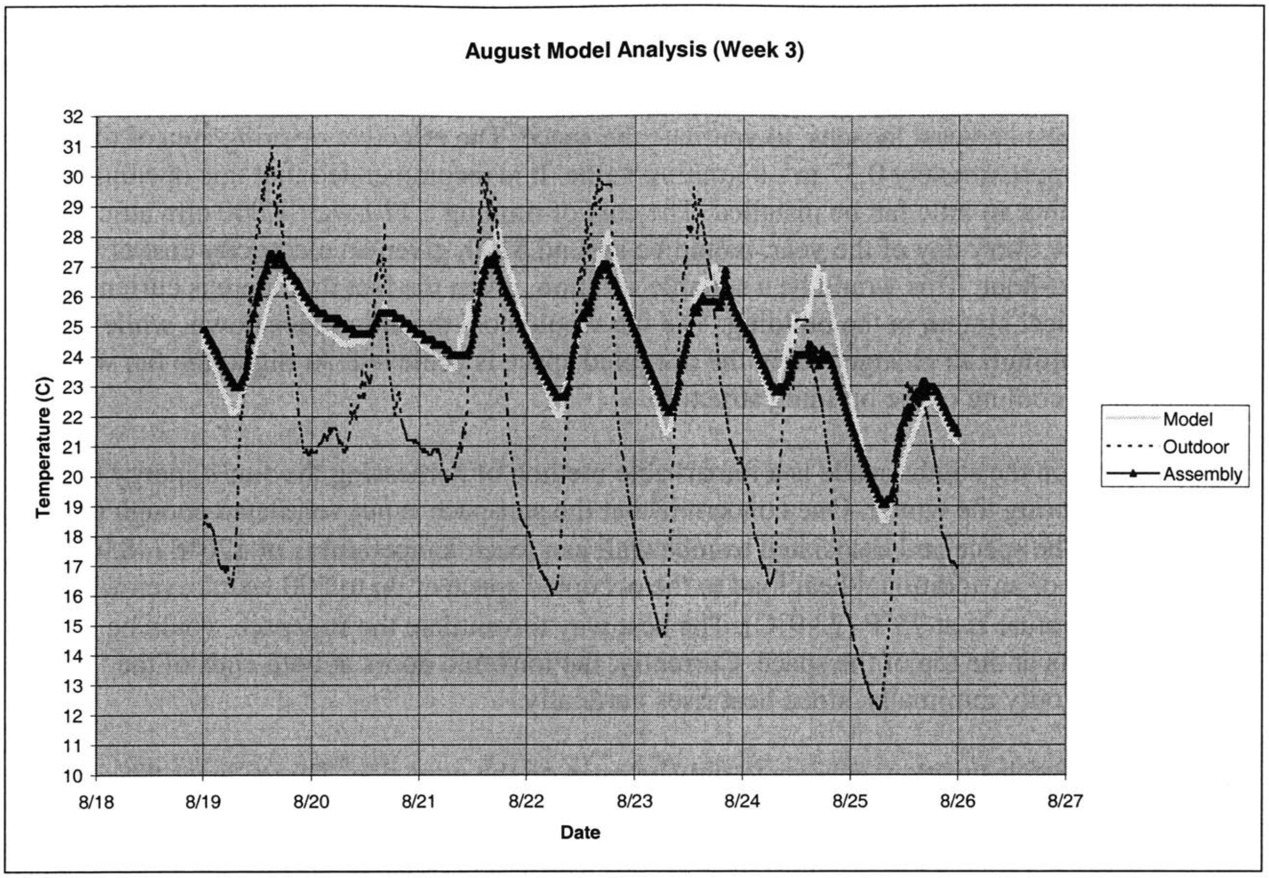


Figure 222 Comparison of model predication to actual indoor temperature data for the third week of August 2001.

Once again, the model shows excellent simulation capabilities. The error is higher than typical on August 24. On this particular day, the predominant winds were from the north. Since there are no direct openings on the north side of the building, the airflow model likely under-predicts the actual ventilation rate. It appears that the estimates of cloud cover fair well.

6.5 Recommendations and Observations

As expected, the basement remains significantly cooler than the main floor. The thermally massive floor and underlying bedrock are effective in absorbing heat gains throughout the day. The main floor also remains comfortable, although ventilation is perhaps not as effective as it could be. As originally sited, it was envisioned that air would flow from the west, into and through the building, and out the louvered door on the east. Because the building's longer side is parallel to predominant winds, the amount of actual cross flow is more limited than if the building's shorter side were parallel to the predominant wind direction. The reason for this is that air takes the path of least resistance and distance. The distance air has to travel around the building is not much more than the distance it has to travel through the building. If the building were rotated 90 degrees, air would have to travel a greater distance going around the building than through the building; hence, cross ventilation is more effective.

The Broadmoor site enjoys average wind velocities of 10 mph (4.47 m/s), with gusts up to two times this value. At night, there is typically not much wind. In this case, the building relies on the stack effect, both through the opening to the attic from the main floor and through the louvered doors on the west and east facades, to ventilate the space. The effective opening area of the vent to the attic is approximately 0.37 m^2, a limiting value. It is recommended that this opening be increased and that an attic fan be installed. The cost of running a 120-watt 1,000 cfm attic fan 24-hours a day, for every day of the year, would be around $100, given an electricity cost of 10 cents a kilowatt-hour. This would be a suitable solution, given the fact that there is currently no active mechanical system in the building. The fan would cool the attic space down, while also ensuring a minimum air change rate in the occupied space is achieved. At night, the fan would enhance night cooling of the building structure.

The sunspace on the south façade is a remarkable method of harnessing the sun's energy to heat the building during the winter. One concern is that the sunspace is not ventilated enough during the summer. The space and associated trombe wall can reach temperatures of 120°F (48.9°C), with the result of an additional heat load to the occupied space of up to 500 watts, even when the outside temperature is at 75°F (23.9°C). The best way to ventilate the sunspace would be to add additional vents at the top of the space. Currently, the louvered doors at both ends of the sunspace help only minimally, since heat rises vertically.

The cupola, upon inspection, appears to only be open on the west side. This reduces the effectiveness of stack ventilation. When wind is blowing from the west, air actually moves downward, causing warm air from the attic to reenter the occupied main floor. Opening up the remaining three sides of the cupola would allow wind to enhance the stack affect, by creating a slight negative pressure like one would create when blowing over the end of a straw.

A proposed idea is to reverse the direction of the fan that directs hot air from the sunspace into the bedrock underneath the basement floor. Some additional ductwork would have to be installed to connect the end of the sunspace fan duct to the main floor fans. One potential problem of this strategy is the potential of bringing radon and moldy air into the main space. Another problem is removing too much "coolth" from underneath the bedrock. Too much heat transfer to the bedrock could raise the temperature of the basement adversely, causing it to reach temperatures higher than normal. The system would be out of balance and continually increase in peak temperature with each daily cycle.

Another option is to reverse the operation of the fans that bring warm air from the sunspace into the main occupied space. This should be done with all windows and vents closed. The idea of this is to draw cooler air from the basement to the main floor.

Currently, the north windows in the assembly room are not opened. This is done with the thought that opening them would reduce the effectiveness of cross ventilation. The windows should in fact be open. Because wind comes from the southwest, the leeward side would be the northeast portion of the building. It is most beneficial to have windows perpendicular to the flow of wind open.

Chapter 7
Phillip Merrill Environmental Center Results and Discussion

7.1 Introduction

The availability of the Philip Merrill Environmental Center for evaluation is very appropriate for the overall needs of this project. The center received the United States Green Building Council's first Leadership in Environmental and Energy Design Platinum award. Natural ventilation was specified in the design for use approximately 9% of the year. While the center did not receive LEED points for natural ventilation because it is not specified for use often enough, the center is among the first buildings in the eastern United States to use natural ventilation as a pre-determined cooling strategy.

7.2 Design Methodology

The Washington DC division of the SmithGroup designed the building. This was the first building they had designed with natural ventilation. The dominating design guidelines were taken from the ventilation chapter of the 1997 ASHRAE Fundamentals, as well as from a reference manual provided with Energy-10, a building simulation program [SBIC, 1997]. Among the included guidelines were recommended setpoints of natural ventilation use when the outdoor temperature is between 66 (18.9°C) and 77°F (25°C) and a relative humidity between 20 and 60%.

Natural ventilation is available through the use of a large amount of manually operable windows located on both occupied floors, as well as automated clerestory windows. Occupants are notified that they can open windows through the use of "open window" signs located in each quadrant of the building. Originally, natural ventilation indicator lights were to be placed at every desk; they were subsequently engineered out due to cost.

7.3 Data Summary

Between May 16, 2001 and December 31, 2001, natural ventilation was used for a total 549 hours out of 1,600 possible hours, a usage factor of 34.3%. The number of possible hours was determined based on typical working hours of 8 am until 6 pm, Monday through Friday, excluding holidays. During this period, the indoor temperature was less than 20°C, 0.46% of the time and greater than 25°C, 11.27% of the time. The remainder of the time, the temperature was between 20 and 25°C.

By using basic energy balance equations, as shown in section 6.2.2, we can determine the outdoor conditions that are required to attain a particular indoor dry bulb temperature and relative humidity, for a given air change rate.

It is necessary to determine the external and internal heat loads on the building. The following table summarizes the equipment in the building, as well as their corresponding heat gain.

Location	Heat Source (sensible)	Continuous/ Idle Heat Load	Quantity/ Load Factor	Total Heat Load
First West	People	100 W	14	1,400
	Workstations	145	14	2,030
	Laser Printer	215	1	215
	Copier	1,100	1	1,100
	Lighting (compact)	32	62/0.5	992
	Lighting (hanging)	32	52/0.5	832
	Lighting (workstation)	64	14/1	896
First East	People	100	14	1,400
	Workstations	145	14	2,030
	Laser Printer	215	1	215
	Copier	1,100	1	1,100
	Lighting (compact)	32	52/0.5	832
	Lighting (hanging)	32	46/0.5	736
	Lighting (workstation)	64	14/1	896
Atrium	People	100	2	200
	Workstations	145	2	290
	Laser Printer	215	1	215
	Copier	1,100	1	1,100
	Fax Machine	30	1	30
	Inkjet Printer	50	1	50
	Lighting (hanging)	32	12/0.10	38.4
Second West	People	100	10	1,000
	Workstations	145	10	1,450
	Laser Printer	215	3	645
	Copier	1,100	2	2,200
	Fax Machine	30	1	30
	Inkjet Printer	50	2	100
	Lighting (hanging)	32	284/0.25	2,272
	Lighting (workstation)	64	10/1	640
Second East	People	100	13	1,300
	Workstations	145	13	1,885
	Laser Printer	215	1	215
	Inkjet Printer	50	1	50
	Lighting (hanging)	32	240/0.25	1,920
	Lighting (workstation)	64	13/1	832
Total internal sensible	Equipment, lighting, people	NA	NA	31872
Total internal latent	People	30	53	1,590
Solar Radiation	Peak Fenestration Gain	NA	685 m^2	20,000
Building Conduction	15 °C indoor/outdoor temperature difference	NA	832 m^2	36,400 (windows) 3,000 (wall)
Total Peak Load	Whole Building	NA	NA	92,862 Watts

Table 29 Internal and external heat loads based on survey done on a typical day.

With the above calculated heat gains, we can find the required outdoor conditions to achieve a certain indoor state with natural ventilation.

Condition	In Temp (°F/°C)	In RH	Sensible Heat (Btu/h / Watts)	Latent Heat (Btu/h / Watts)	ACH	Out Temp (°F/°C)	Out RH
Only internal loads	78/25.6	60	110,000/32,238	6,000/1,758	1	57.2/14	≥100
	78	60	110,000	6,000	2	67.6/19.8	85
	78	60	110,000	6,000	5	73.9/23.3	75
	78	60	110,000	6,000	10	75.9/24.4	70
	75	60	110,000	6,000	2	63.6/17.6	≥100
Internal, solar, wall conduction	75/23.9	60	190,000/55,684	6,000	2	57.1/13.9	≥100
	75	60	190,000	6,000	5	67.8/19.9	90
	75	60	190,000	6,000	10	71.4/21.9	85
All loads, including window conduction	75/23.9	60	312,800/91,673	6,000	2	45.5/7.5	≥100
	75	60	312,800	6,000	5	63.2/17.3	≥100
	75	60	312,800	6,000	10	69.1/20.6	95
	75	60	312,800	6,000	30	73.0/22.8	85

Table 30 Required outdoor temperature and relative humidity required for given interior temperature, relative humidity, heat load, and air change rate.

Interestingly enough, we see that humidity is not an issue when you have a building with high interior sensible heat loads. It appears that when accounting for all loads, a suitable target outdoor temperature of 63°F (17.2°C) should be attained when five air changes an hour of ventilation is available. It appears that unless there is very intensive ventilation, it is not possible to cool the building with air at a temperature close to the desired indoor dry bulb temperature. The original high-end setpoint of 77°F (25°C) specified by the architectural engineering firm is too high for this building, with the assumption that there is little thermal mass in the building and that current thermal comfort standards for mechanically ventilated buildings are to be satisfied.

When an outdoor temperature of 63°F is specified as the maximum allowable outdoor temperature for natural ventilation, natural ventilation use was possible for 35.8% of the time between May 16, 2001 and December 31, 2001. The actual usage of 34.4% was very close to this value. When the maximum allowable outdoor temperature is raised to 68°F (20°C), the natural ventilation usage period increases to 43%. Moreover, with the outdoor temperature setpoint at 75°F (23.9°C), the percentage is 74%. This indicates that if a high air change rate is achieved, natural ventilation could potentially be used for a very significant portion of the year, even when the entire summer season is included in analysis.

7.4 Energy Analysis

One of the main reasons for carefully analyzing the outdoor and indoor temperature relationship in a naturally ventilated building is to determine the amount of energy that can be saved over using air-conditioning or other active mechanical ventilation system. An analysis was performed, using a fixed indoor temperature setpoint of 75°F (23.9°C). To simplify analysis, peak internal and solar loads were used. A U-factor of 0.24 $W/m^{2}{}^{\circ}C$ was used for the walls, while 3.54 $W/m^{2}{}^{\circ}C$ was used for the windows. Below we see the net cooling requirement calculated for ten-minute increments for all occupied hours between May 16, 2001 and December 31, 2001. The peak load of 70 kW occurs in mid-August. Note that air-conditioning is still needed until mid-December, with the assumptions used for this analysis. During the analysis period, the net cooling power requirement is 63,049 kW-hr. At 5 cents a kilowatt-hr, the cost of electricity would be around $3,150 dollars. This does not account for chiller coefficients of performance that are typically higher than 1, which would lower the energy estimate. This analysis also does not account for required fan and pump energy, which would increase the energy estimate. From this basic analysis, there is definitely energy and money to be saved in using natural ventilation.

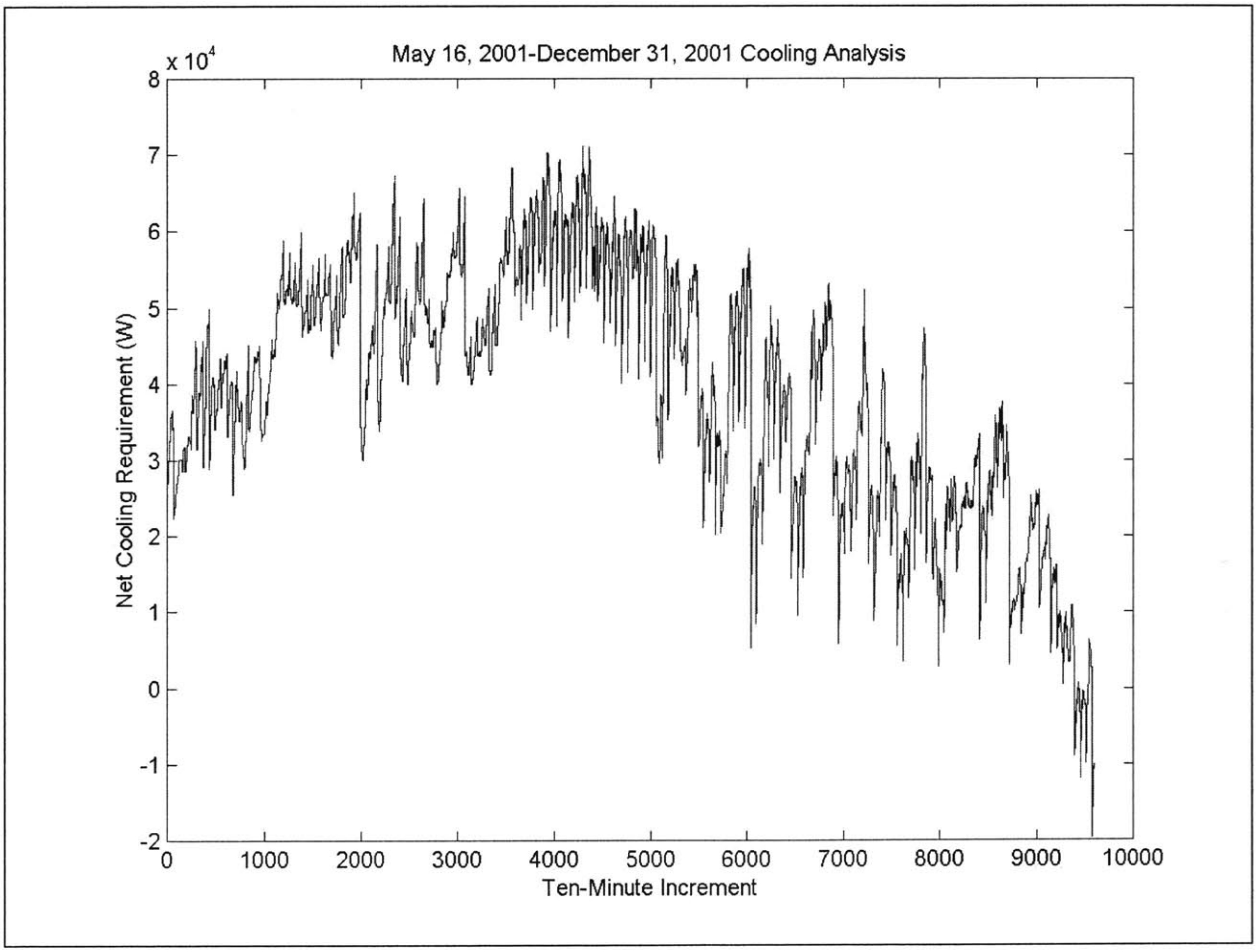


Figure 223 Net cooling requirement between May 16, 2001 and December 31, 2001, based on loads shown in Table 29.

7.5 Natural Ventilation Period Data Analysis

7.5.1 Temperature

Temperature measurements taken in the Philip Merrill Environmental Center shed significant light on the way occupants operate windows and vents. Analysis is provided in the following plots and discussion. Although temperature is one of the easier parameters to measure in a building, it is still important to properly place sensors. Sensors were located away from direct heat sources and also shielded from solar radiation.

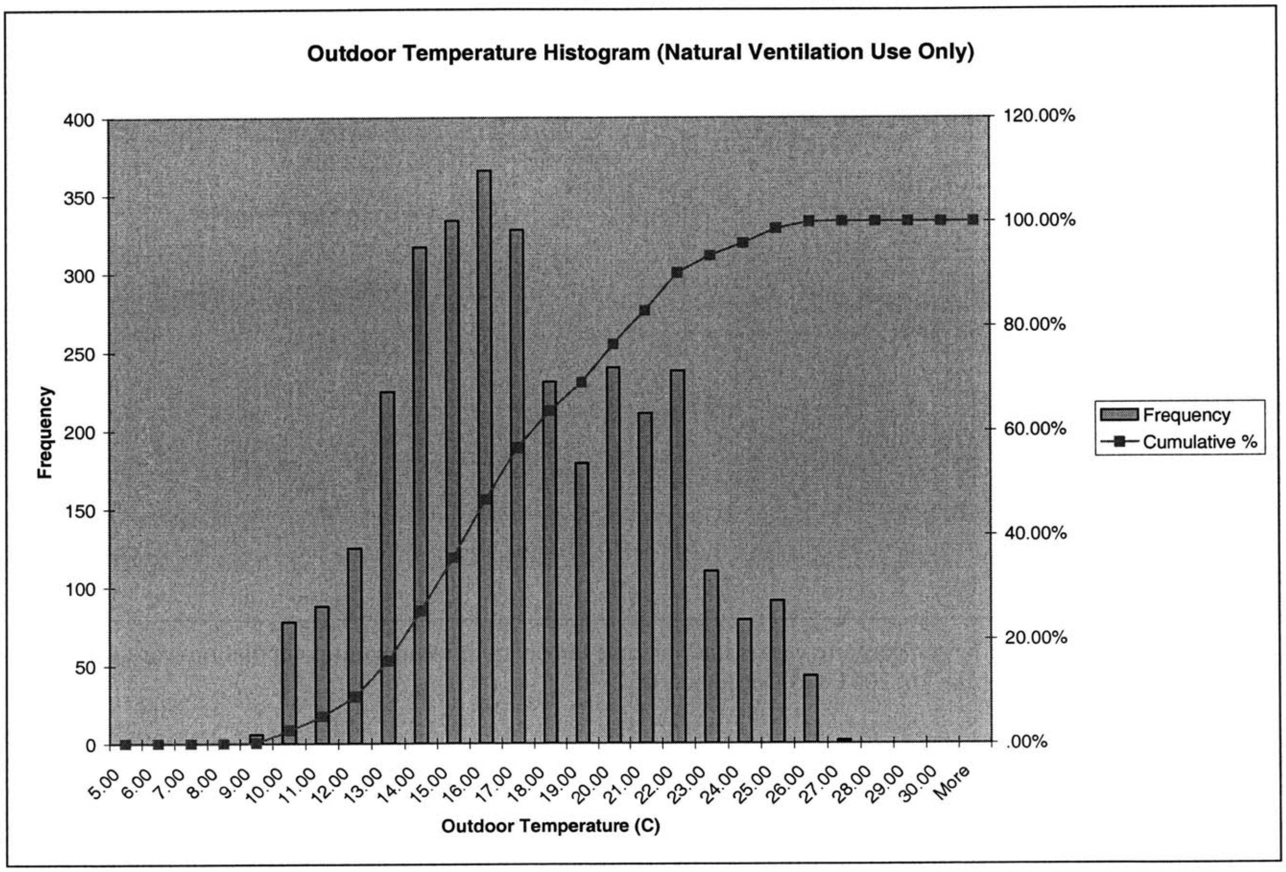


Figure 224 Histogram of outdoor temperature between May 16, 2001 and December 31, 2001, when natural ventilation was used during occupied hours.

When natural ventilation was in use, the range of outdoor temperatures extended from 9 to 26°C (48.2 to 78.8°F), with the majority of usage when the temperature was below 23°C (73.4°F). This range of temperatures is lower than originally specified by the architectural engineering firm. The original range proved to be too narrow and did not take into account significant internal heat loads and that occupants would not open windows fully, due to excessive draft.

The majority of the natural ventilation system is operated manually. The clerestory windows, which are out of the reach of occupants, are the only windows that are motorized and automated. These windows are linked to the building management system and automatically open when temperature and humidity sensors reach a predefined range for natural ventilation. The chillers are locked out automatically when this occurs. At one time during experimentation, there was a software bug that forced the clerestory windows to open and close every five minutes.

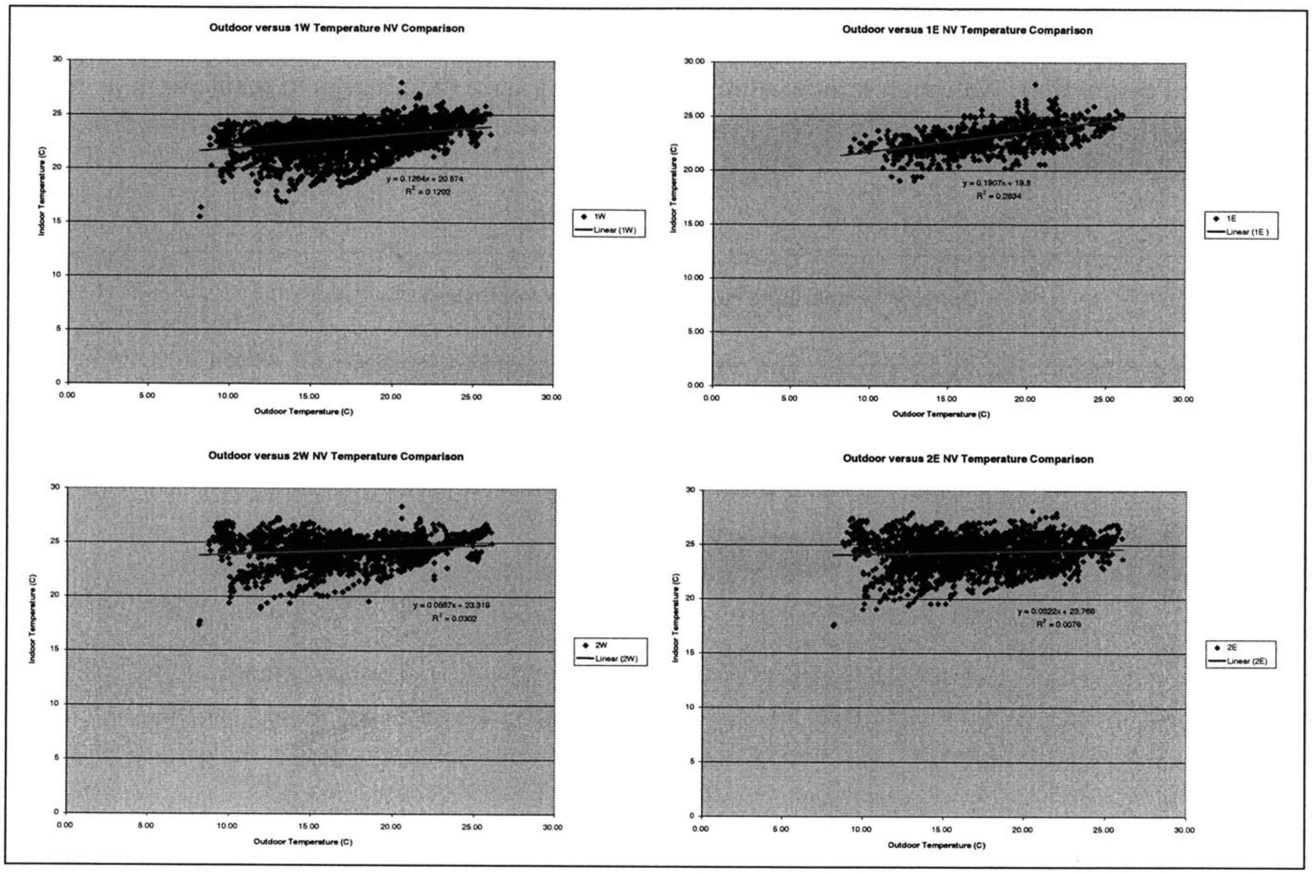


Figure 225 Plots of outdoor temperature versus interior zone temperature when natural ventilation was used during occupied hours, between May 16, 2001 and December 31, 2001.

In all zones, there is only slight correlation between indoor and outdoor temperatures. At lower outdoor temperatures, most of the time, the indoor temperature is less than 25°C. This is a good indication that occupants operate windows effectively to keep indoor temperatures within a specific comfort zone. For the first floor, the range extends from 20 to 25°C. For the second floor, the range extends from 22 to 26°C. An average of all four zones shows a similar trend. It appears that the first floor stays on average 1 to 2°C cooler than the second floor. This is an expected effect of having both floors openly connected by a passageway along the south façade.

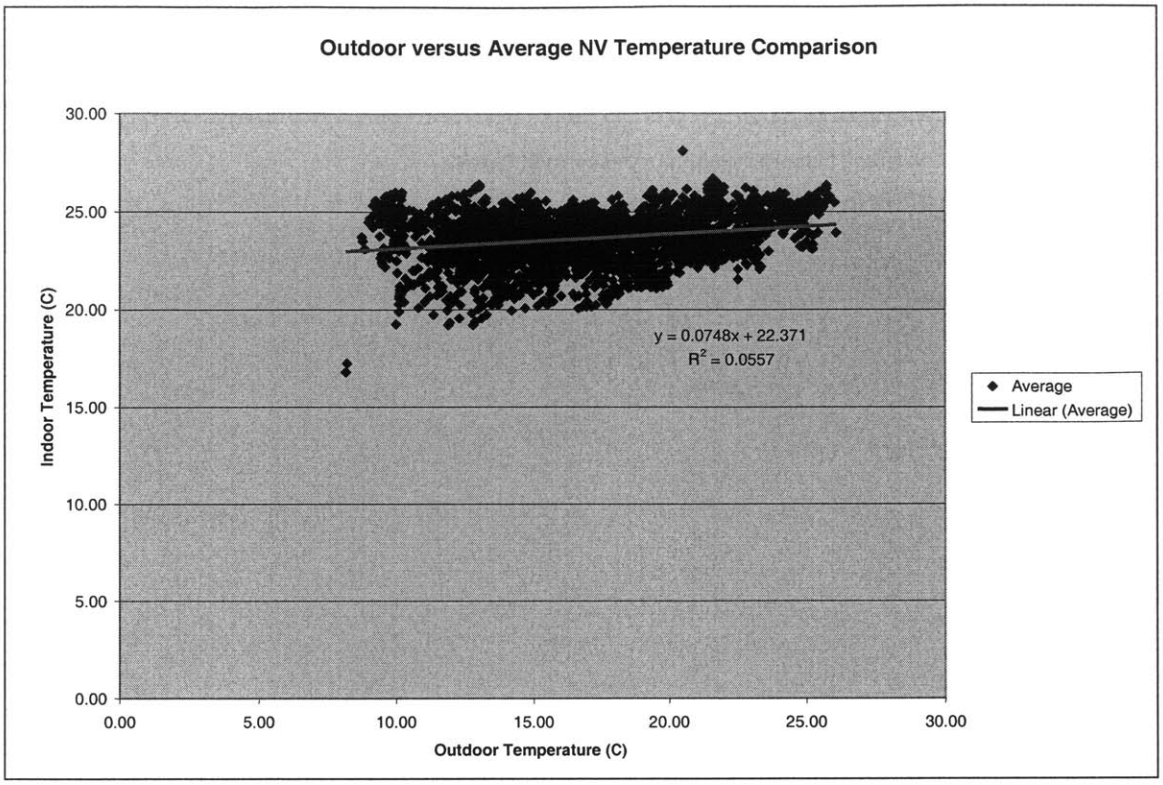


Figure 226 Outdoor temperature versus averaged indoor temperature when natural ventilation was in use.

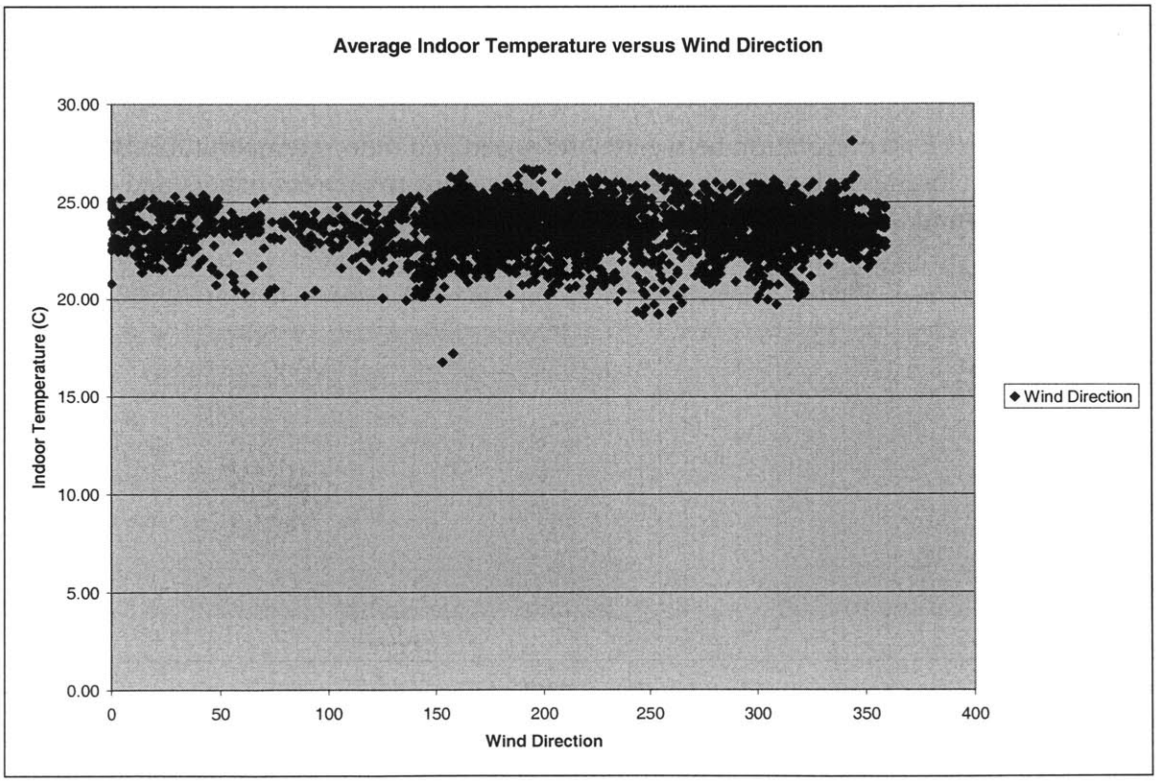


Figure 227 Average indoor temperature versus wind direction when natural ventilation was in use.

There appears to be no correlation between wind direction and the indoor temperature. Once again, this is an indication that occupants adjust windows as conditions change.

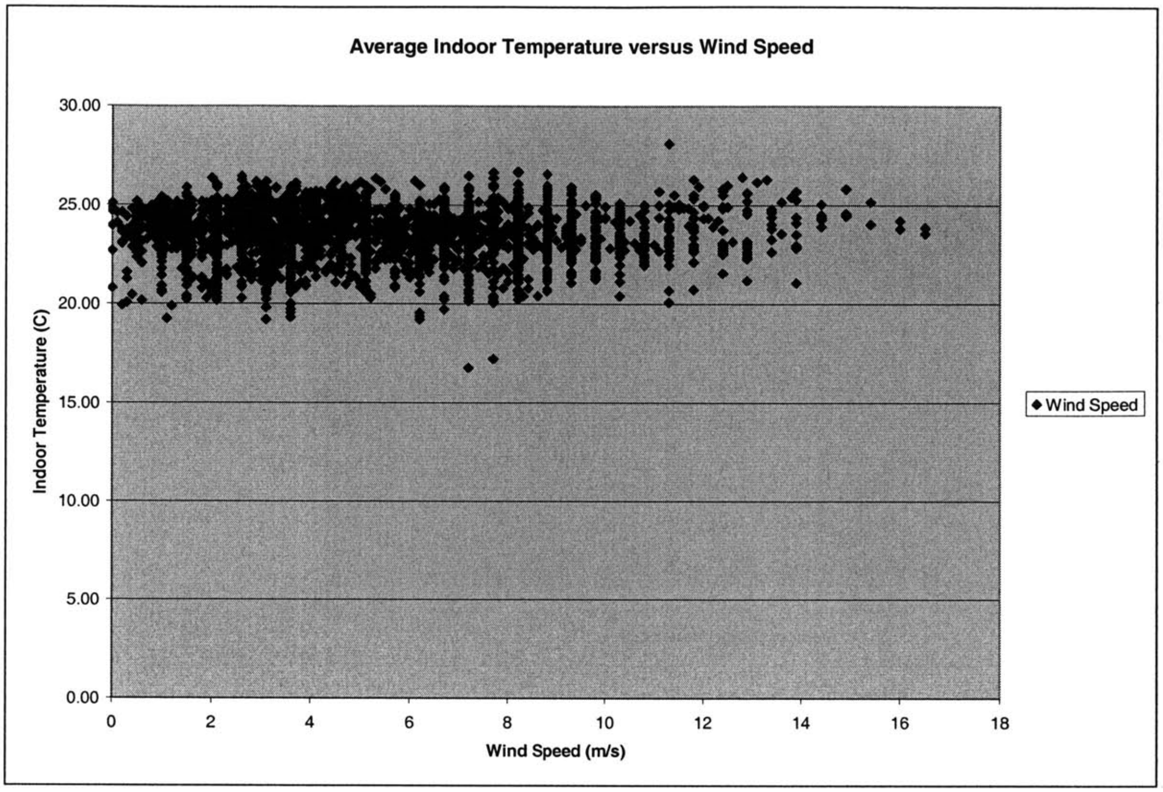


Figure 228 Average indoor temperature versus wind speed when natural ventilation was in use.

Again, there appears to be no correlation between wind speed and indoor temperature. Building occupants most likely closed windows during higher wind speeds to prevent papers and other objects from flying around.

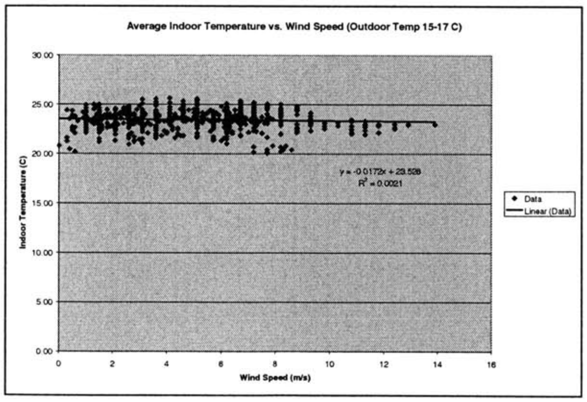


Figure 229a Average indoor temperature versus wind speed for outdoor temperature between 15 and 17°C.

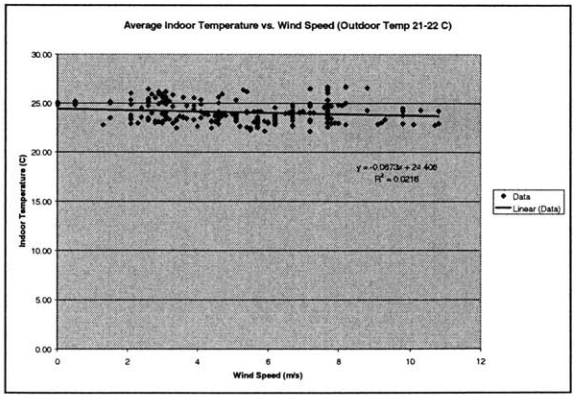


Figure 229b Average indoor temperature versus wind speed for outdoor temperature between 21 and 22°C.

The previous wind versus indoor temperature analysis was likely too general to provide very much meaningful information. To address this, average indoor temperature versus wind speed for outdoor temperature within a narrow range is shown in Figure 229. We see that there is once again little correlation between wind speed and indoor temperature when natural ventilation is used. This reemphasizes that occupants are perhaps not opening windows as much as they could, due to draft.

There are two natural ventilation fans in the building. One is rated at 2,800 cubic feet per minute (equivalent to 1.9 ACH for the second east zone) and is located on the north side of the second floor. The other is located on the north side of the first floor and is rated at 5,400 cubic feet per minute (equivalent to 5.4 ACH for the first east zone). The fan on the first floor was typically not used, except on the hottest days, when natural ventilation was in use. The second floor fan was used whenever natural ventilation was specified for use. The plot of data below shows that the air passing though the second floor fan is usually several degrees higher than outdoor temperature, as one would expect. The few points where the temperature drops below 20°C are likely days when the fan was not running; a backdraft of outdoor air is the cause for the low temperatures. This prompted further investigation of the second floor fan; it appears that the damper on the fan does not fully close automatically when the fan is off. When the fan turns on, it only opens to approximately 30%, appearing to drastically reduce airflow.

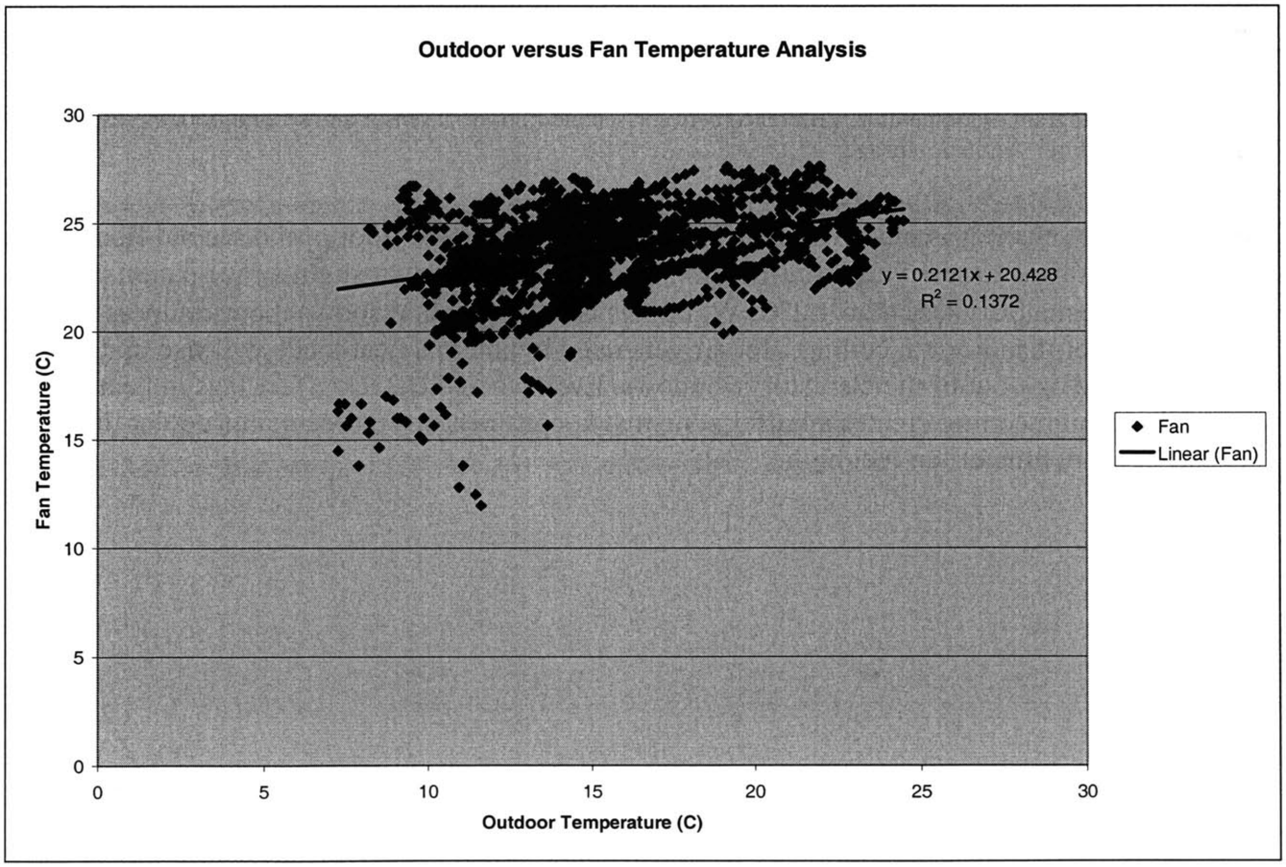


Figure 230 Outdoor temperature versus second floor fan temperature.

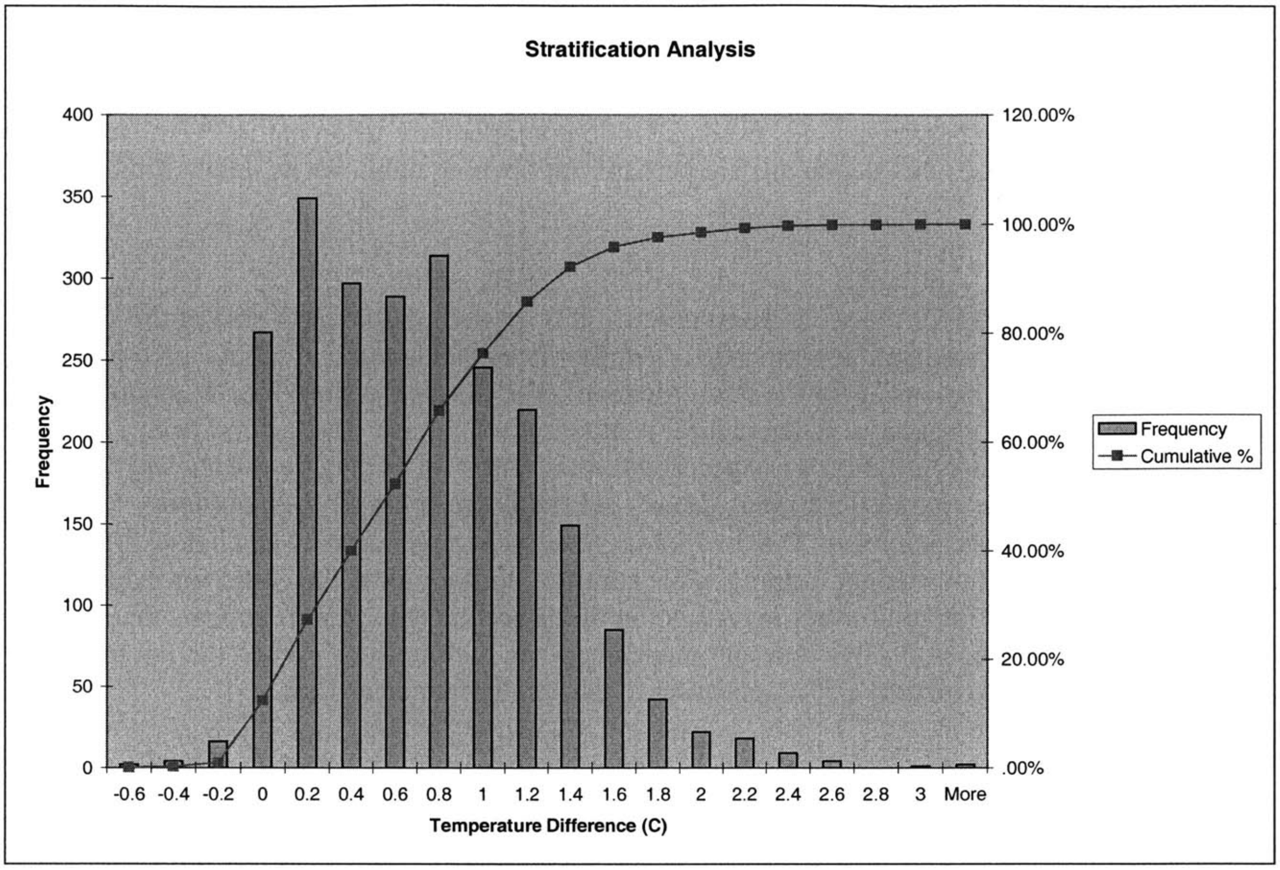


Figure 231 Histogram of temperature difference between second floor desk sensor and second floor clerestory sensor during natural ventilation usage.

A temperature sensor was placed approximately 15 feet above the floor of the second floor's east wing. The goal was to see if any stratification existed. It appears that slight stratification does exist, with the majority less than 1.2°C. While this is fairly small, it shows the usefulness of having a higher than normal ceiling. Hot air generated by internal heat loads will rise up towards the ceiling and exit out of the clerestory windows. Even when the stack effect lags in heat removal, the high ceiling creates a buffer zone that keeps the heads of occupants cooler than if the ceiling were nine or ten feet high.

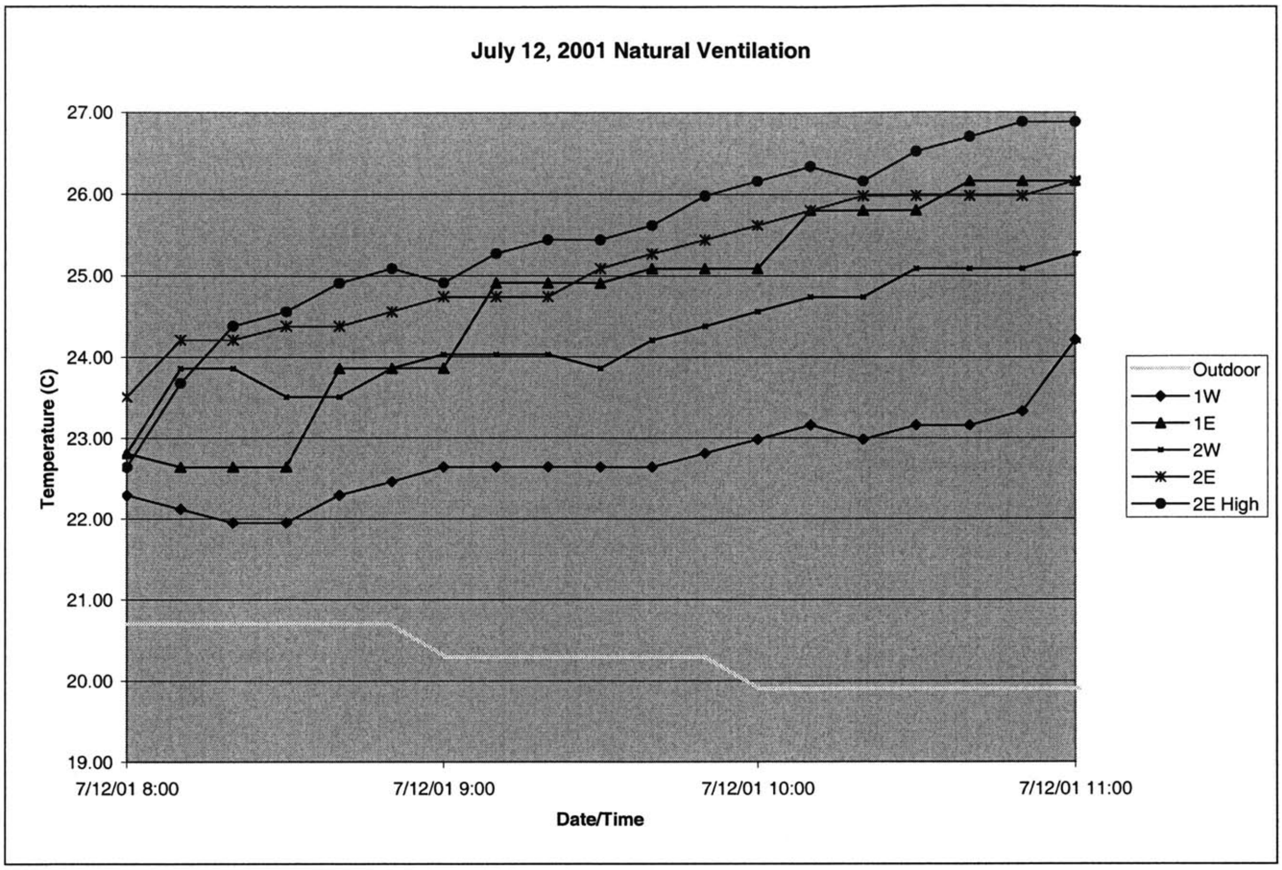


Figure 232 Plot of temperatures on July 12, 2001, when natural ventilation was in use.

On July 12, 2001, the positions of all windows was carefully noted and controlled. Winds were predominantly from the west at 2.6-4.6 m/s. We see that natural ventilation was not able to tame the internal and external heat gains on the building, even though the outdoor temperature dropped. Because the predominant wind direction was not perpendicular to the south façade, the air change rate was likely fairly low. Overall, the east side of the building stayed warmer than the west side. The main reason for this is that there are more windows on the west side of the building. Also, because winds were from the west, the west portion of the building received more actual airflow. The east portion of the first floor was likely in the most disadvantageous position, since it is isolated from the west portion of the building by walls.

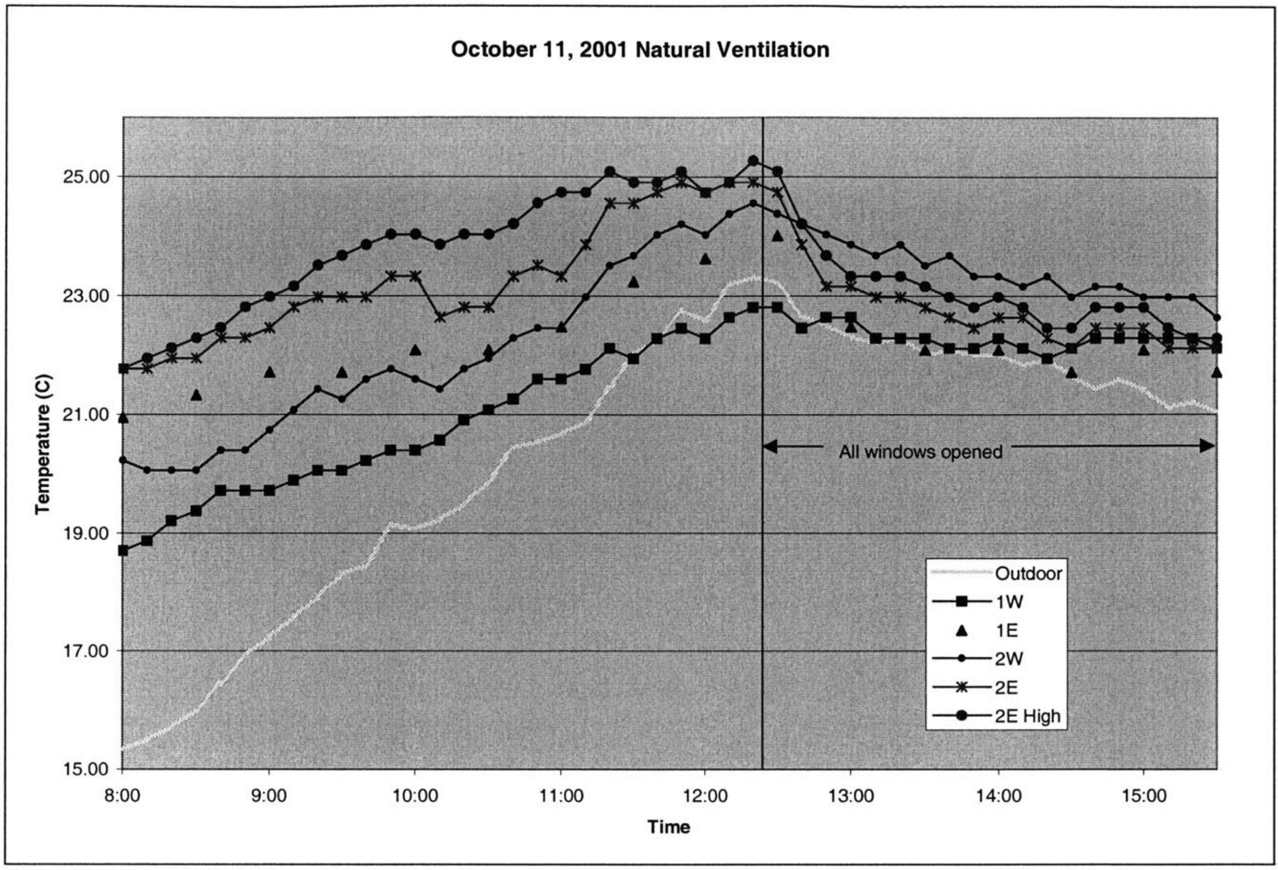


Figure 233 Plot of temperatures on October 11, 2001, when natural ventilation was in use.

On October 11, 2001, natural ventilation usage was possible for the entire day. The predominant wind direction was from the south, with values ranging from 5.9-8.6 m/s. It was not until 12:20 pm that all windows in the building were opened. The response of the building to this took place rapidly. 30 minutes later, the building's interior temperature dropped by as much as 2°C on the east side of the second floor. The response on this day contrasts dramatically with the response on June 12, 2001. Higher wind velocities at favorable directions can cool this particular building reasonably well. Although earlier wind analysis showed little relation between speed and indoor temperature, when data is looked at on a micro-scale hour-by-hour basis, some interesting trends, like the one seen above, can be found.

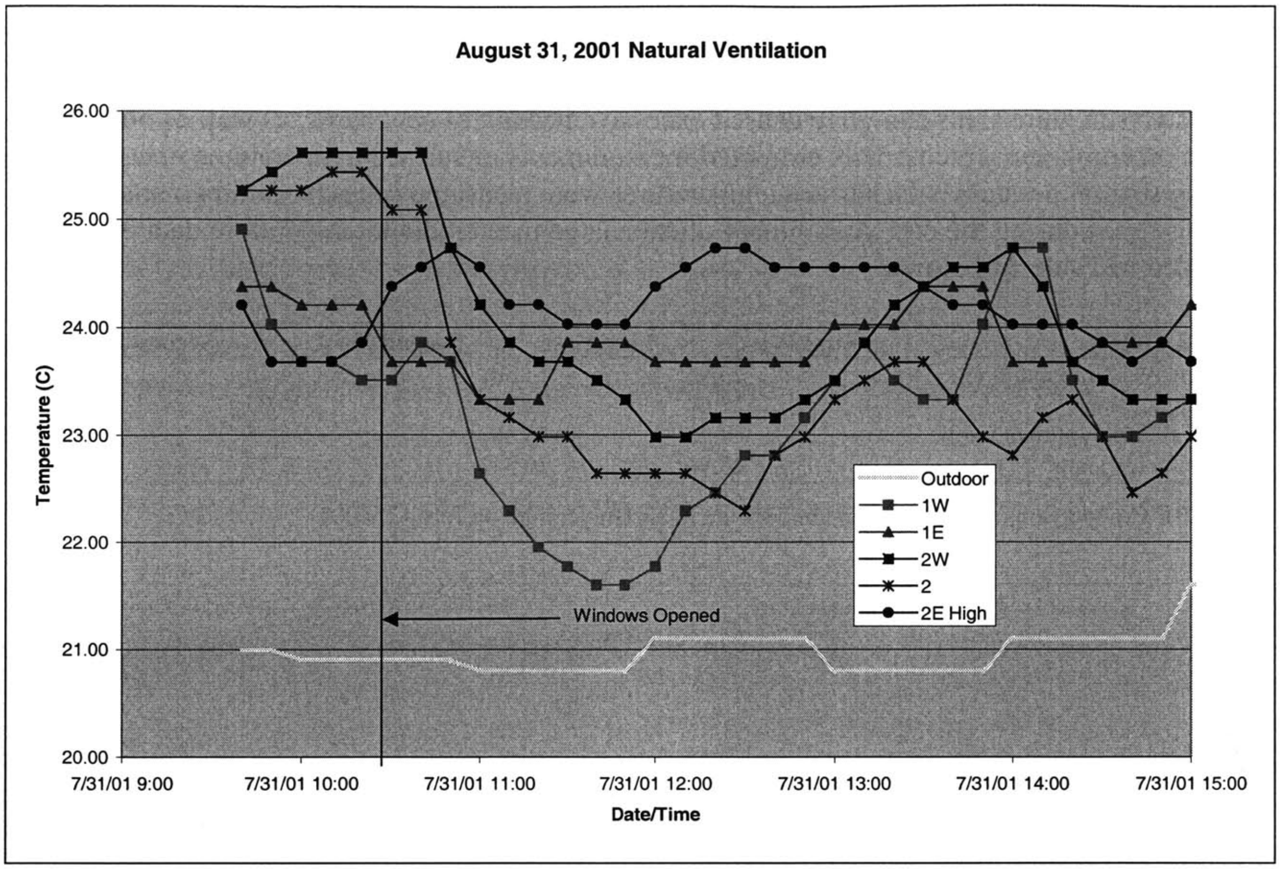


Figure 234 Plot of temperatures on August 31, 2001, when natural ventilation was in use.

On August 31, 2001, natural ventilation was used on a fairly cool summer day. The predominant wind direction was from the east, with wind speeds between 0.8 and 4.4 m/s. In previous discussion of data from July 12 and October 11, the status of windows was verified with an on-site visit. On August 31, there was no such visit and thus we infer from the data when natural ventilation was used. It appears that windows were opened around 10:30 in the morning. In 30 minutes, there is a drop-off in temperature of up to 1.5°C on the second floor. The temperature continues to drop on the second floor, while the temperature of the east side of the first floor levels off. In surveys of occupants in that section of the building, windows are often closed, due to excessive draft. It should be noted that occupants on the first floor have more control over windows, in general, than occupants on the second floor. Occupants on the first floor operate windows on the south façade for both floors.

7.5.2 Mean Radiant Temperature

When the building first opened in December of 2000, there were significant complaints of excessive sun glare. This sun glare caused excessive heating of occupants, as well as obscured vision on computer screens. This prompted measurements of surface temperatures in each space. During several on-site visits, surface temperatures were measured in each building zone at various times during the day. A summary of calculated mean radiant temperature data is provided in Table 31 below.

July 12, 2001	First West	First East	Second West	Second East
Morning mean radiant temp.	23.96	24.80	24.75	25.60
Morning air temp.	22.64	24.91	24.03	24.74
Afternoon mean radiant temp.	24.75	25.88	25.65	26.60
Afternoon air temp.	23.86	26.34	25.27	26.07

Table 31 Comparison of mean radiant temperature to air temperature on July 12, 2001.

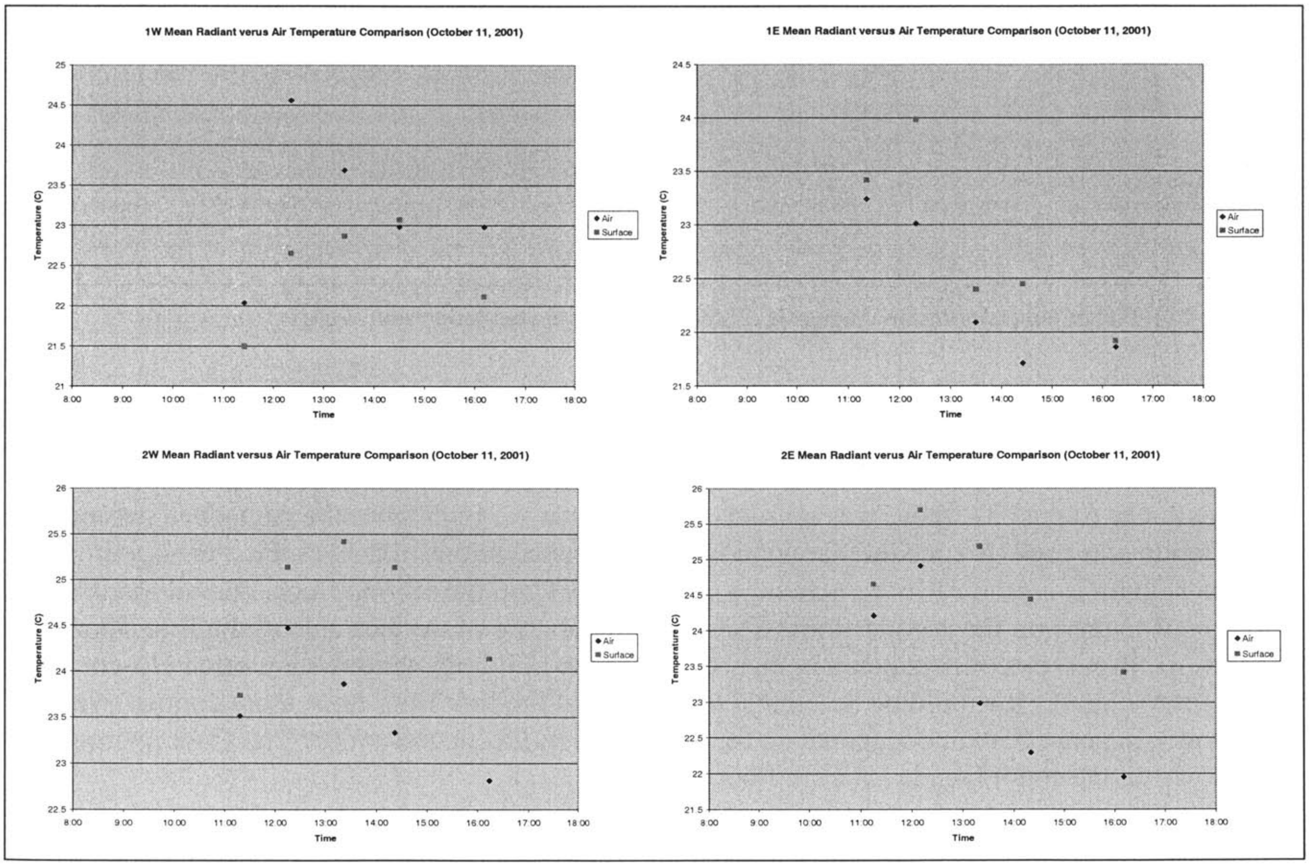


Figure 235 Comparison of mean radiant temperature versus air temperature for each building zone on October 11, 2001.

It appears that the averaged surface temperatures in the space do not vary much from the corresponding air temperature. Once again, this is expected in a building with a fairly light thermal mass structure. High levels of wall and ceiling insulation also help temper the effect of solar gains on exterior surfaces during the day.

7.5.3 Relative Humidity

Indoor relative humidity is an important consideration in determining the thermal comfort occupants will feel. We note that outdoor relative humidity was found not to be as important a consideration, unless air at a higher temperature than the indoor temperature setpoint is brought in from the outside. An analysis of the indoor relative humidity between May 16, 2001 and December 31, 2001 is provided in the following histogram. Overall, the indoor humidity levels remained reasonable. Not surprisingly, a lack of moisture was more prevalent than excessive moisture, due to high sensible heat loads.

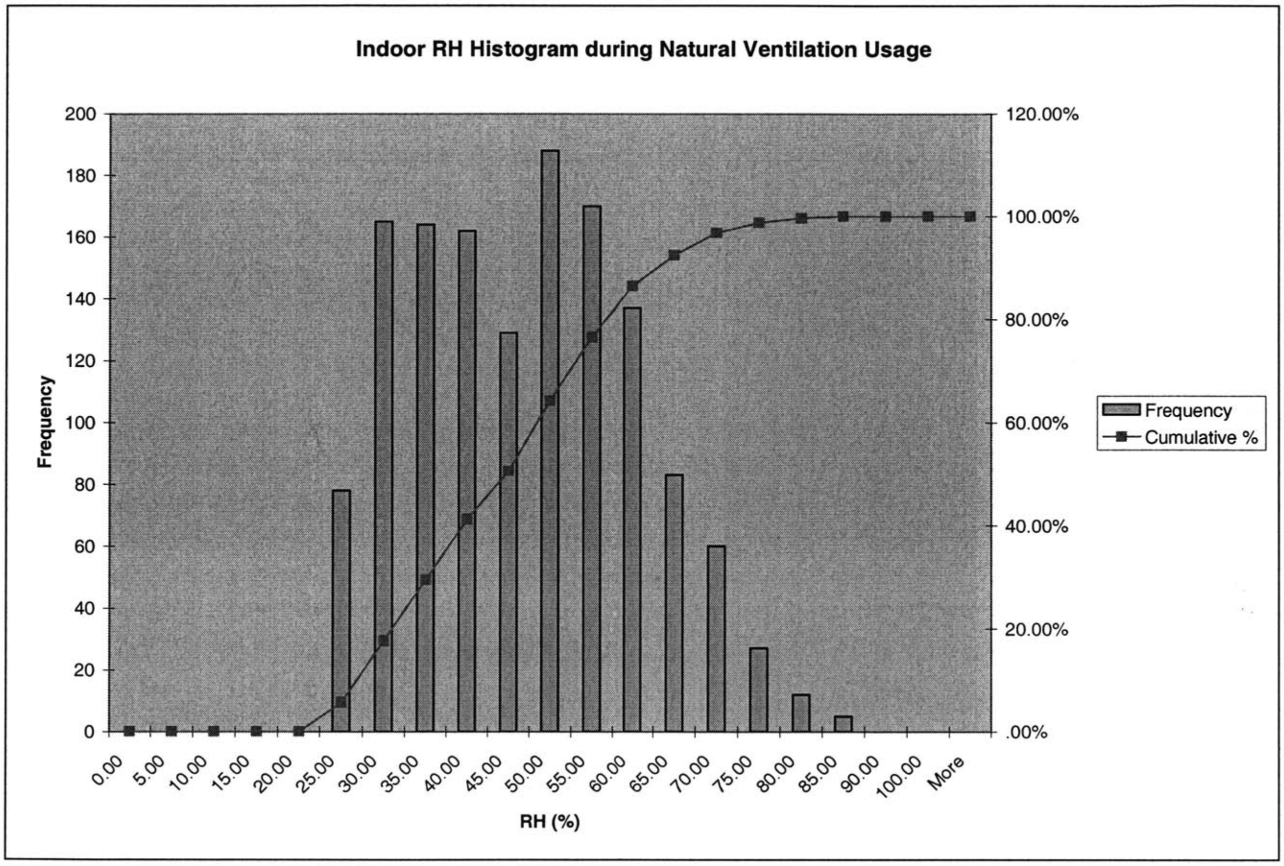


Figure 236 Histogram of indoor relative humidity between May 16, 2001 and December 31, 2001 for natural ventilation use during occupied hours.

7.6 Air-Conditioning Data Analysis

The Philip Merrill Environmental Center enjoys the availability of low-energy geothermal heat pumps to run its cooling system. With a high coefficient of performance, the cooling system, when used with natural ventilation, can provide optimal comfort at a minimum of energy consumption, compared to traditional office buildings. It is important to compare the actual air-conditioned temperature in each zone of the building, to the setpoints used by the building management system. It would appear that the level of air-conditioning could affect occupant's perception of thermal comfort when natural ventilation is used. For example, if occupants are used to air-conditioning running at a setpoint of 70°F (21.1°C), natural ventilation running up to 75°F (23.9°C) may not be tolerable because of difficulty in adapting to a significant temperature difference.

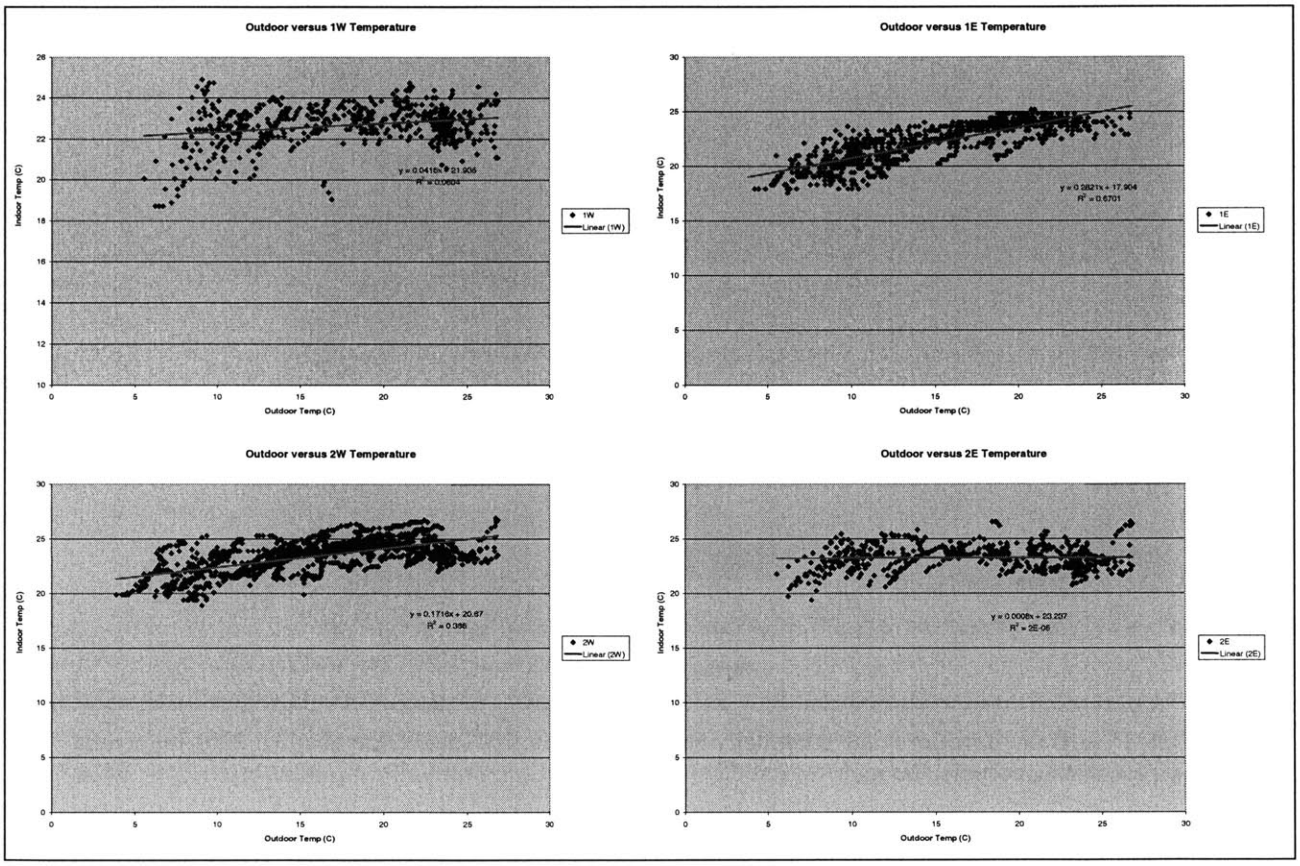


Figure 237 Outdoor temperature versus zone temperature when air-conditioning was in use during occupied hours between May 16, 2001 and December 31, 2001.

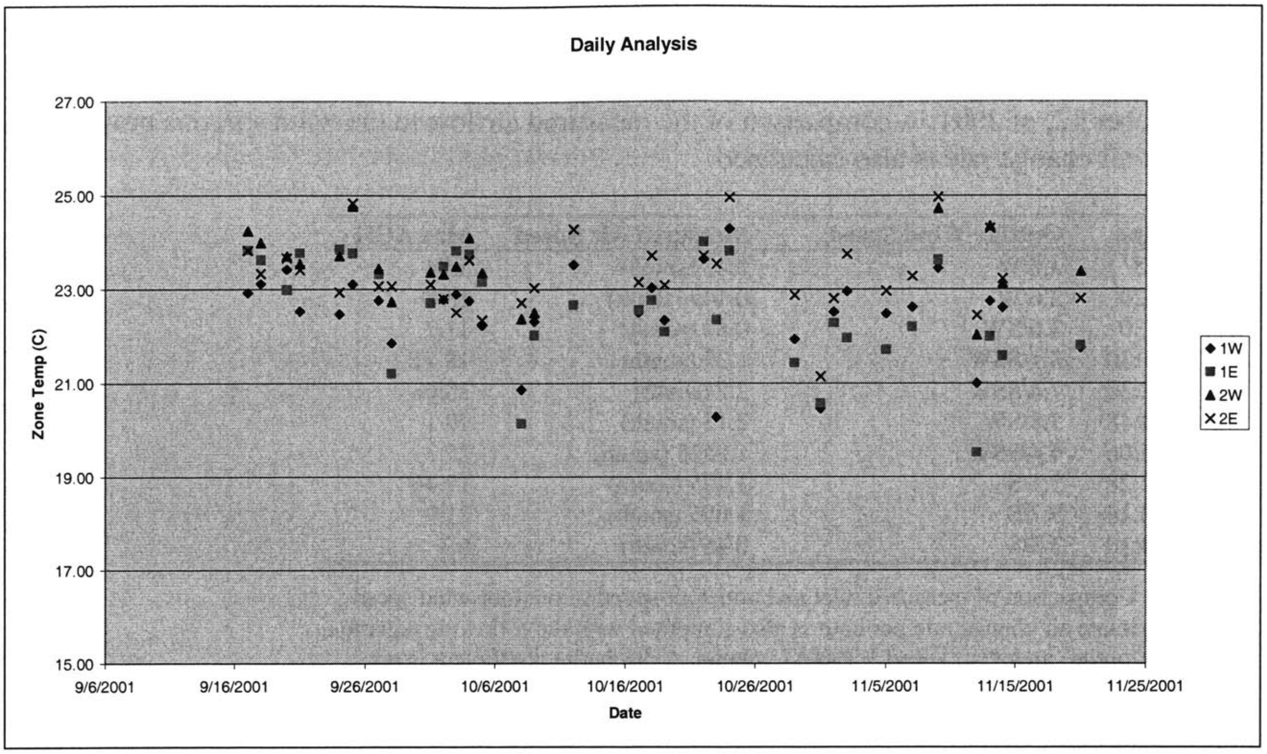


Figure 238 Daily average zone temperatures when air-conditioning was in use between May 16, 2001 and December 31, 2001.

It appears that air-conditioning maintains a fairly consistent temperature throughout the building, except for some exceptions during early morning periods. Strangely enough, there seems to be some correlation between indoor and outdoor temperature in some regions of the building, specifically, the west section of the second floor and the east section of the first floor. An explanation for this can be found in the variability of the amount of fenestration in each of these sections, as well as the placement of the temperature control sensors providing feedback to the building management system. This could be an indication of a control system with temperature sensors placed in locations adversely affected by solar radiation.

Overall the system appears to operate around 23 or 24°C, which is consistent with settings in the building management system. In Figure 237, we see that the range of temperatures exhibited closely follows the range of temperatures seen during natural ventilation usage. Occupants are using natural ventilation in a way that creates a thermal environment close to that experienced when air-conditioning is used. It appears that there is a difference in thermal comfort expectations between a mixed-mode building and a building that is wholly naturally ventilated. Expectations of indoor temperatures are different if air-conditioning is still available for direct comparison.

7.7 Air Change Rate

Detailed airflow measurements with a handheld anemometer were taken on July 12, October 11, and October 12, of 2001. A comparison of the measured airflow to the wind speed is provided. A resultant air change rate is also calculated.

Date/Time	Outside Wind Speed	Measured Air Speed	Max ACH
7-12/8:15	3.6/W	0.42 (south)	5.74
7-12/10:20	2.6/W	0.145 (south)	1.98
7-12/11:30	3.6/SW	0.82 (south)	11.2
10-11/11:30	8.1/SSW	1.37 (south)	18.71
10-11/12:30	7.4/SSW	2.2 (south)	30.04
10-11/13:48	5.8/SW	2.13 (south)	29.1
10-11/15:06	4.4/SSW	1.8525 (south)	25.3
10-12/12:28	5.1/S	1.425 (south)	19.46
10-12/13:14	5.7/S	1.605 (south)	21.9
10-12/14:10	3.7/S	0.46 (south)	6.7

Table 32 Comparison of measured inlet and outlet air speed to outdoor wind speed. An approximate air change rate per hour is also computed with the following equation (min[inlet, outlet] area * air speed * 3600) / volume. A discharge coefficient is not included in the calculation, because anemometer readings were taken past the vent/window.

The airflow model predicts an air change rate of 16.3 to 20 air changes per hour for October 11, 2001. This compares favorably with the air change rate calculated from the measured window air speed. Airflow measurements at windows were tricky, since wind direction and wind speed are always changing. The typical velocity measured at any opening was on the order of 1 m/s, with peaks at 3 m/s. The wind speeds measured at the Thomas Point Lighthouse were on the order of 3 to 4 times greater than the measured window air speeds. It is also likely that wind coming from the bay experiences a dramatic change in speed when it hits land. It is possible that having an open garage below the two main floors minimizes the available wind pressure for cross ventilation. Air velocities inside the interior spaces of the building were too small to measure accurately, unless there was a significant gust of wind.

7.8 Thermal Comfort

While recorded temperature data gives an insight into how well windows are being used to maintain a suitable interior space temperature, it is the comfort of occupants that ultimately determines if a ventilation strategy is successful. Between September 17, 2001 and November 20, 2001, fifteen occupants were asked to rate their thermal sensation twice a day using the following scale: (-3) cold, (-2) cool, (-1) slightly cool, (0) neutral, (+1) slightly warm, (+2) warm, (+3) hot.

Sex	First West	First East	Second West	Second East	Atrium
Female	2	3	3	3	2
Male	1	0	1	0	0
Total	3	3	4	3	2

Table 33 Physical distribution of surveyed occupants by gender.

At any given time, there are approximately sixty people in the building. It may be noted that the survey test sample features many more females than males (87/13 ratio). The female to male ratio in the building, as a whole, is around 75/25. In the east section of the first floor, there is only one male. The highest concentration of males exists on the west section of the first floor, the location of computer and information technology personnel. It is a typical trend for environmental groups in the United States to attract more female employees [Census, 2000].

In plots below, the Fanger PMV model described in Chapter 5 was used with input parameters of 50% relative humidity, a clothing insulation value of 0.5, a metabolic rate of 100 W/m^2, and an indoor air speed of 0.1 m/s. The typical clothing ensemble of workers consists of a short-sleeved shirt and slacks or skirt. The typical activity level falls between standard office work and walking.

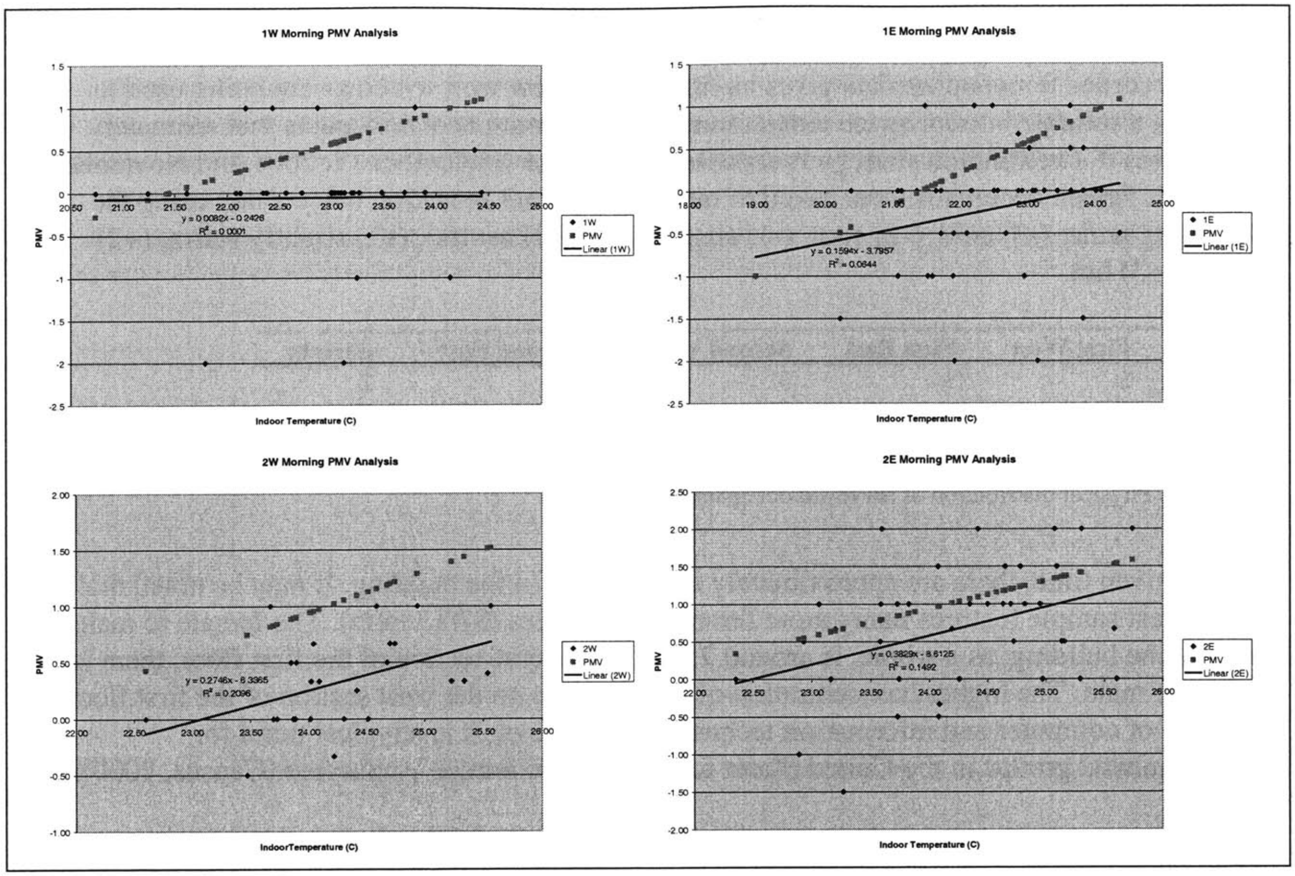


Figure 239 Plots of morning zone temperatures versus thermal comfort survey thermal sensation (TS) indices and Fanger model predicted mean votes (PMV).

During the morning, occupants rarely feel thermal discomfort when natural ventilation is used. Most rated thermal sensations are below +1, indicating a slightly warm sensation. The exception occurs on the second floor's east zone. The likely reason for this is the availability of fewer windows, effectively reducing the air velocity available to enhance evaporative cooling. Bathrooms and mechanical systems primarily block the east portion of the north wall. The natural ventilation fan appears undersized to compensate for the lack of windows.

The Fanger model again appears to deviate from what was indicated by occupants on their surveys. There is a possibility for discrepancy based on differences in clothing levels and surface temperatures though. Also, since the rated thermal sensations were taken twice a day, they may not be a reflection of a person's changing thermal comfort from minute to minute. For example, occupants were asked to rate their thermal sensation at 10 am and 3 pm each day. Earlier in the day, it may be cooler than at 10 am. Likewise, at 3 pm it may be warmer than at 1pm. It should be pointed out that the slope of the collected data for the second floor matches the slope of the Fanger predictions very well.

One conclusion to be drawn from this data is that people feel more comfortable with natural ventilation at a given interior temperature, in comparison to air-conditioning. Again, it should be noted that there is a degree of uncertainty as to the exact clothing level and activity level of occupants surveyed. Changing one or more input parameters could shift the Fanger curve to match the recorded occupant data.

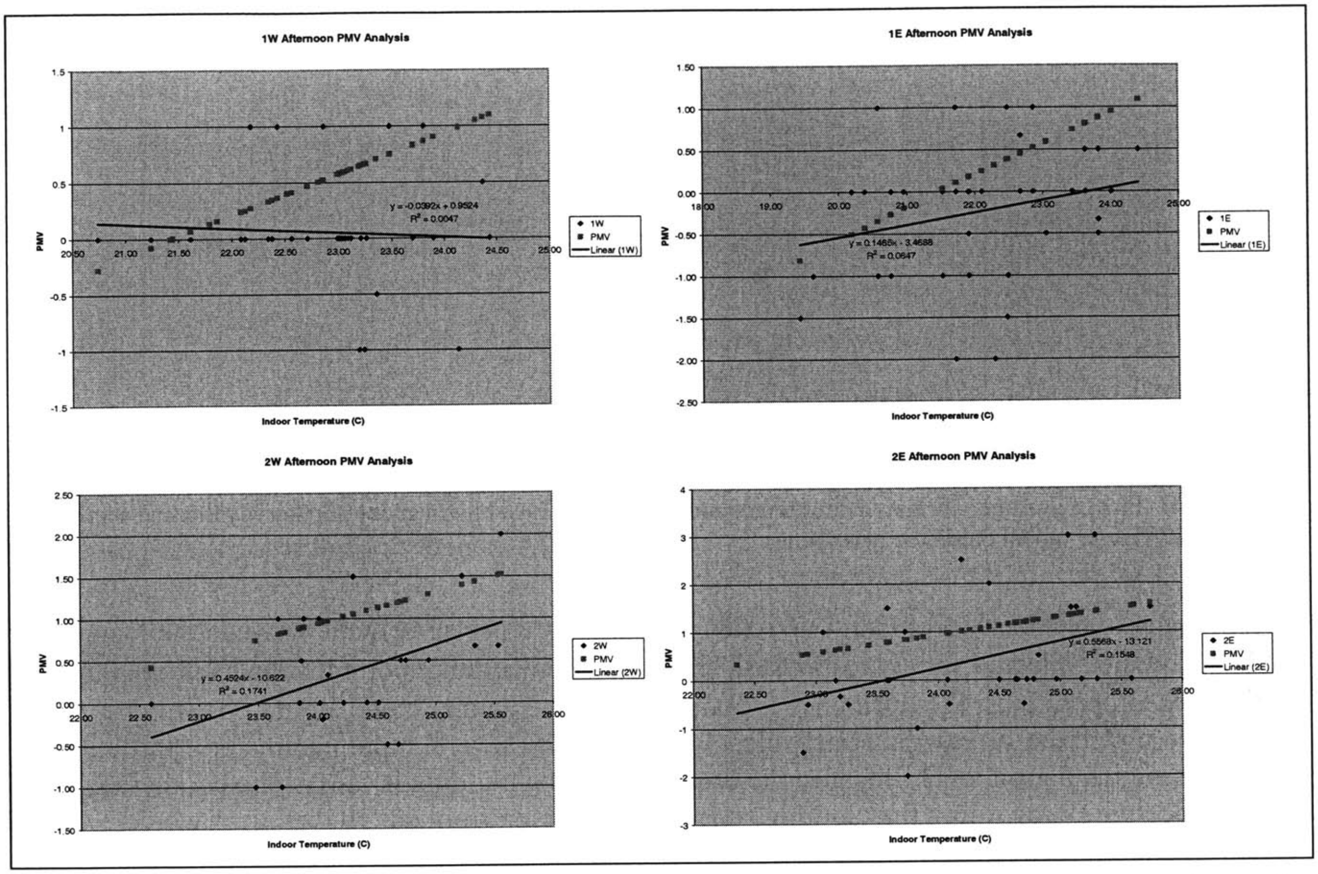


Figure 240 Plots of afternoon zone temperatures versus thermal comfort survey thermal sensation (TS) indices and Fanger model predicted mean votes (PMV).

In the afternoon, occupants on the first floor rarely feel excessively warm. They are more likely to feel cool. On the second floor, there are occasional times when occupants feel hot; once again this occurs on the east side where there are fewer operable windows. The Fanger model appears to predict the slope of thermal comfort responses very well on the second floor, while there is much less correlation on the first floor.

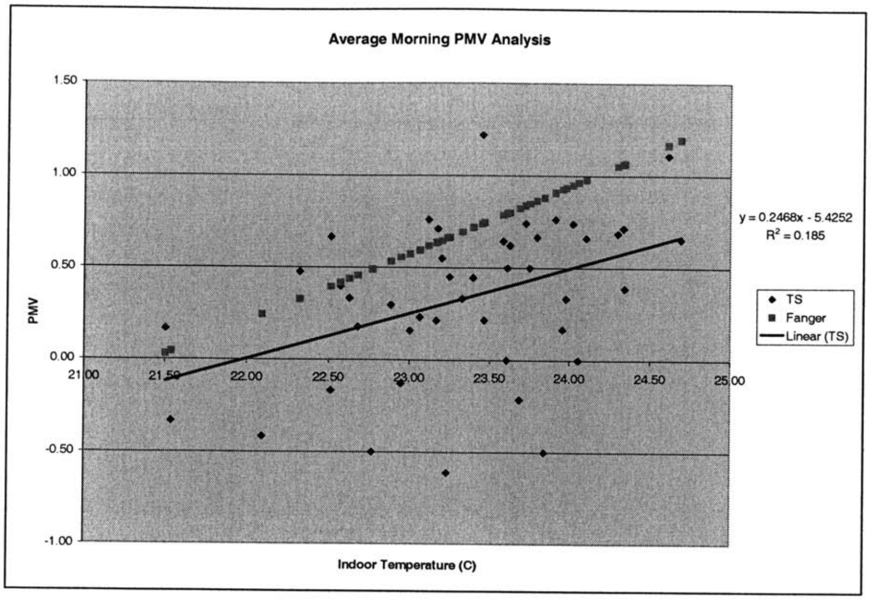


Figure 241 Plot of average morning indoor temperature versus averaged thermal comfort survey thermal sensation indices and Fanger model predicted mean votes.

An average of responses from all four zones shows fairly close agreement between the Fanger model and the collected survey responses. The neutral temperature point differs by about 0.5°C. At higher temperatures, the difference is about 1.5°C. The Fanger model could possibly be shifted to match the survey data fairly closely by changing several input parameters, particularly the clothing insulation level. Because the dress code at the building is fairly relaxed, there is some uncertainty regarding the clothing style of each person from day to day, than would typically be found in an office building.

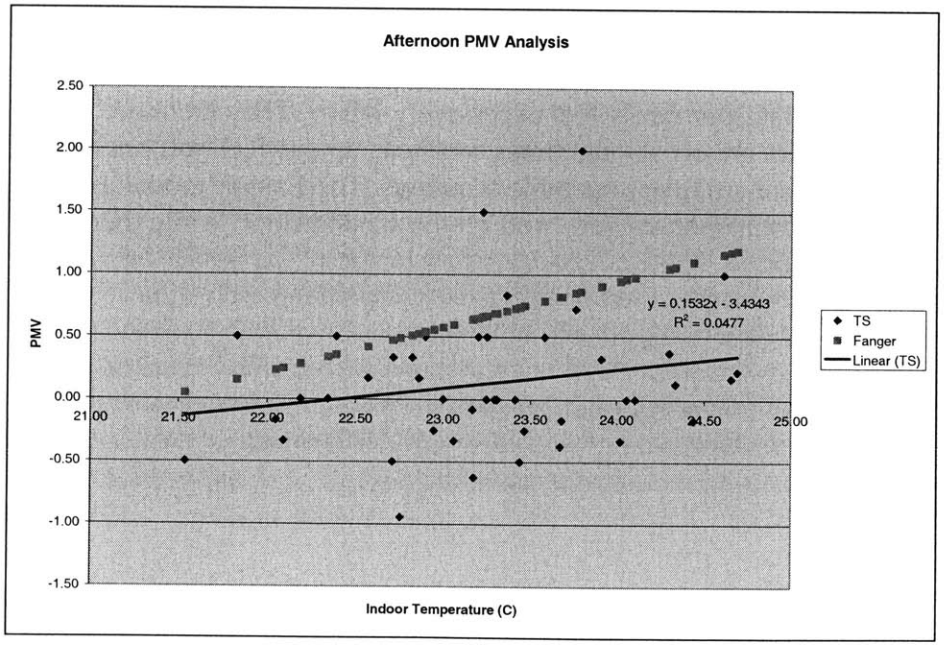


Figure 242 Plot of average afternoon indoor temperature versus averaged thermal comfort survey thermal sensation indices and Fanger model predicted mean votes.

In the afternoon, there is slightly more separation between the survey data and the Fanger model, than for the morning case. The neutral temperature point differs by about 1°C; at higher temperatures, the difference is about 2°C. With thermal sensation values averaged, occupants appear to have only felt more than slightly warm on two days. The interesting thing is that this occurred on days when the temperature was similar to levels provided by air-conditioning. This merits additional analysis by collecting more thermal comfort data on days when air-conditioning is used.

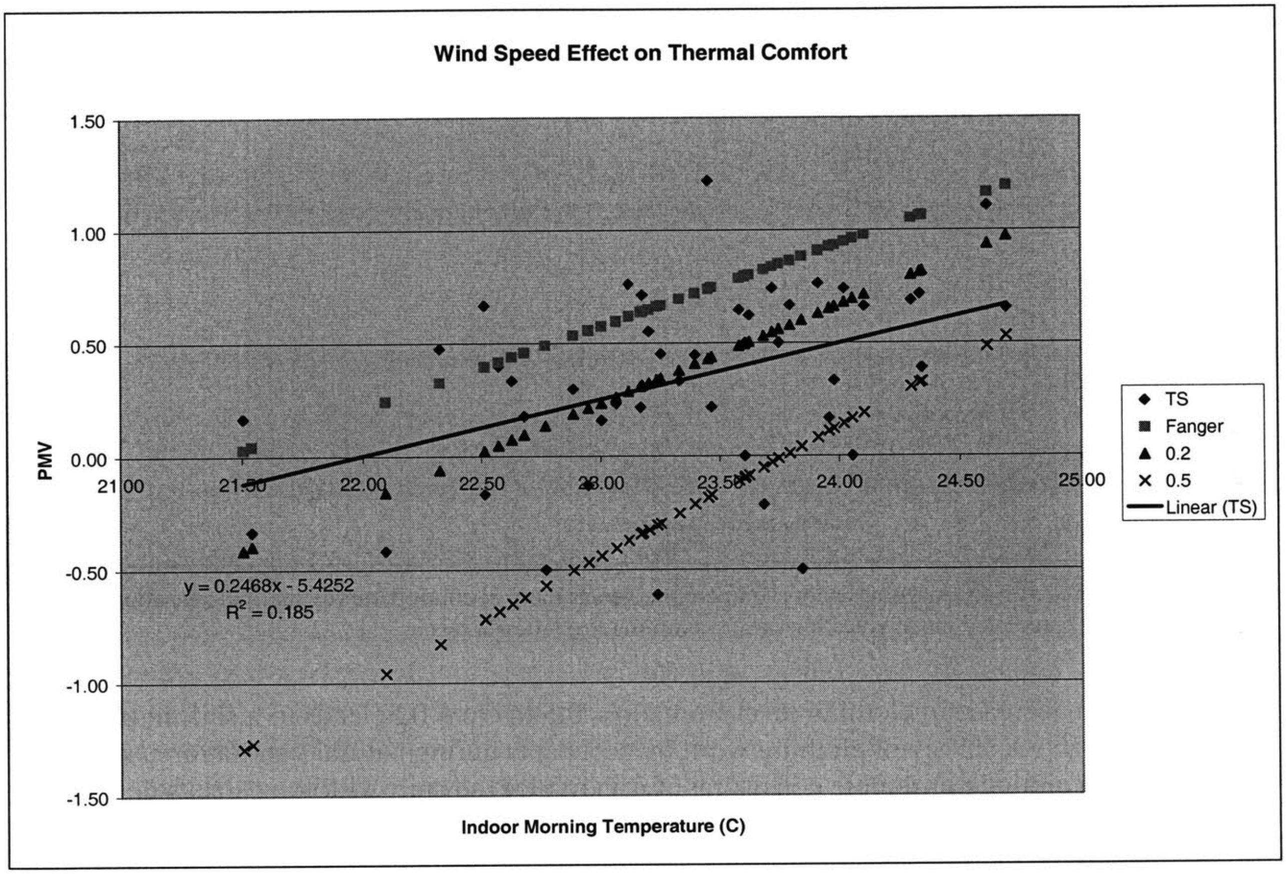


Figure 243 Plot of average morning indoor temperature versus thermal comfort survey thermal sensation indices and Fanger model predicted mean votes for various indoor air speeds (0, 0.2, and 0.5 m/s).

An increase in air-velocity shifts the Fanger curve significantly to the right. Indoor air velocities were measured during several site-visits. They were never more than 0.2 m/s in the center of each zone, except at points close to the windows. In those cases, the maximum measured air velocity was typically under 2 m/s, with a steep drop off 3 meters from the window. At 0.5 m/s, the Fanger model estimates that occupants would be more comfortable at higher temperatures than indicated by the collected occupant data. What is not indicated by this data analysis is that air coming into the space may be cooler than the overall zone temperature. Thus, there is a draft risk for those close to the windows. While some people in the center of the space would benefit from a 0.5 m/s air velocity, most likely the 0.5 m/s velocity occurs at the windows where the overall air is cooler.

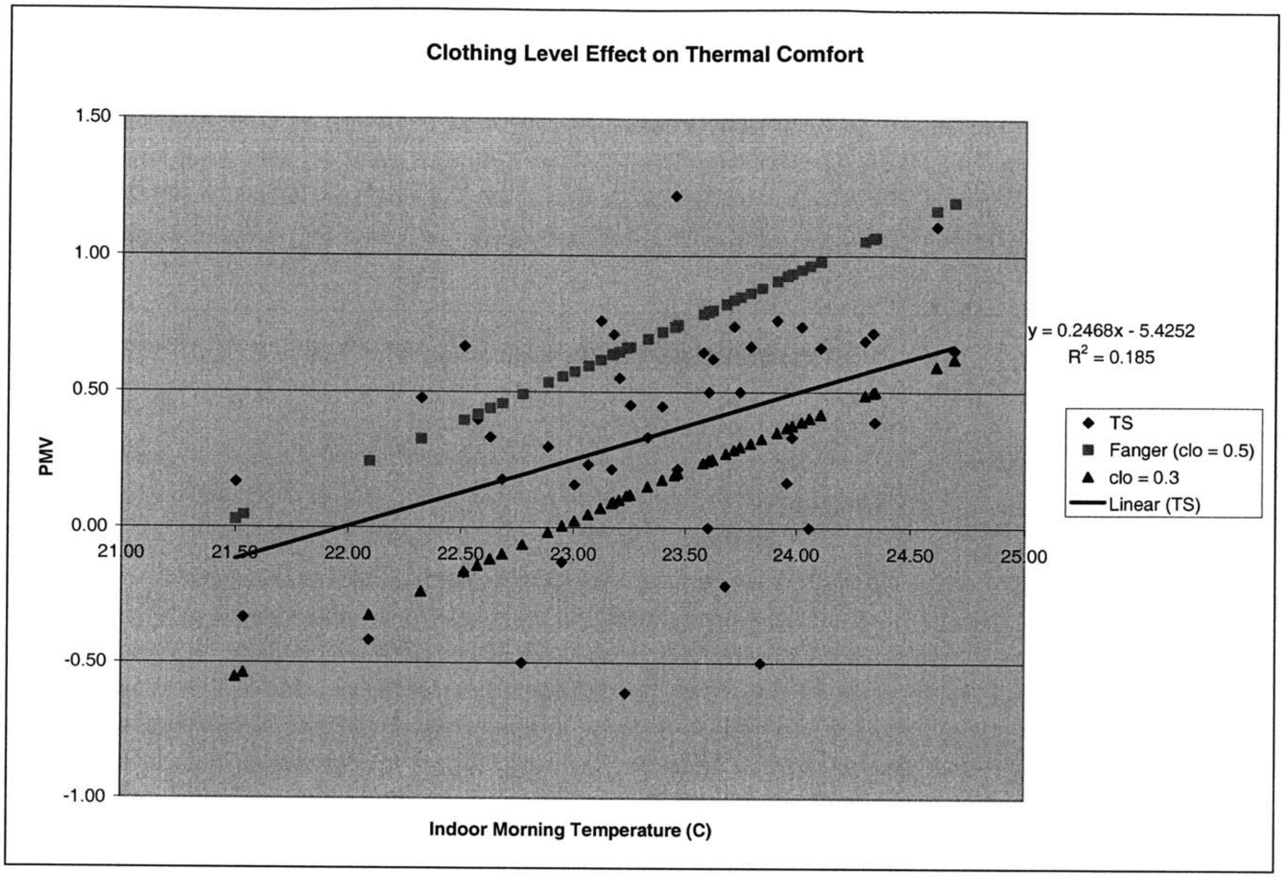


Figure 244 Plot of average morning indoor temperature versus thermal comfort survey thermal sensation indices and Fanger model predicted mean votes for various clothing insulation levels.

As expected, a decrease in clothing level from clo = 0.5 to clo = 0.3, leads to a shift in the Fanger curve to the right. A survey of clothing worn by occupants during natural ventilation usage revealed that a clothing ensemble consisting of a short-sleeved shirt with long slacks or a skirt was most common. This corresponds to a clo value of 0.5. A clo value of 0.3 corresponds to a clothing ensemble of both short-sleeve shirts and shorts. While the dress code of the Chesapeake Bay Foundation is relaxed, most occupants maintain a business casual dress style.

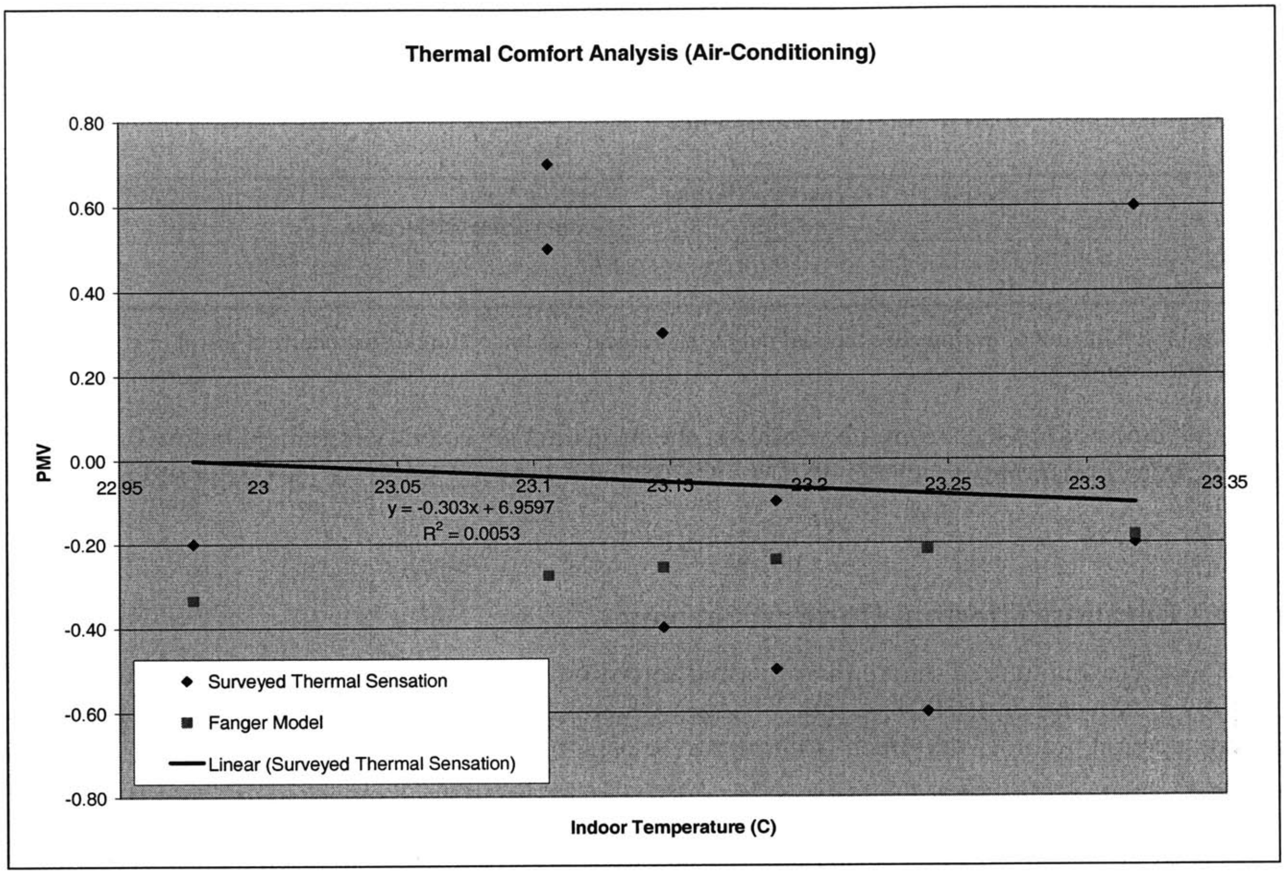


Figure 245 Analysis of thermal comfort during use of air-conditioning between September 15, 2001 and November 20, 2001.

During the thermal comfort survey period, air-conditioning was used on 6 days out of 32 surveyed days. In the figure above, we see that occupants were on a whole satisfied with conditions provided by the air-conditioning. The Fanger model approximates the thermal response fairly well. We must keep in mind that only six days of data are available, so any statistical analysis should be viewed with care. Another point is that people's perception of air-conditioning during the fall may be different from their perception during peak temperature and humidity days during the summer. This ties in with the concept of adaptive comfort: during the summer, occupants may be tolerant of higher indoor temperatures. Likewise, during the fall, they may prefer slightly cooler temperatures.

Another thing to notice is a smaller overall difference between the Fanger model and survey data for this building, in comparison to the results for Broadmoor. This is likely because an interior temperature of 78°F (25.6°C) was never exceeded, whereas temperatures reaching towards 90°F (32.2°C), were seen at Broadmoor. The Fanger model appears to breakdown at high temperatures outside the ASHRAE summer comfort zone.

7.8.1 Other Thermal Comfort Parameters

Other important measures of thermal comfort include: asymmetric thermal radiation, vertical air temperature differences, warm or cold floors, and draft. An analysis of predicted percentage dissatisfied is provided in the following table:

	Asymmetric Thermal Radiation	Vertical Air Temperature Difference	Warm or Cold Floors
July 9	<1%	<1%	6%
October 11	1.5%	<1%	6%

Table 34 Evaluation of asymmetric thermal radiation, vertical air temperature difference, and warm or cold floors, for thermal comfort.

At a distance of ten feet from the windows, the measured air velocity remained below 0.2 m/s. At 25°C, this corresponds to a PPD of 10%. At 20°C, the PPD is 15.6%. At 15°C, the PPD is 21.1%.

7.8.2 Detailed Thermal Comfort Surveys

The workers that agreed to rate their thermal sensation were also asked to fill out a more detailed survey in November of 2001. A total of seven general questions were asked. The answers for each question did not vary much from person to person.

The first question asked workers to evaluate how often they operate windows close to them. As would be expected, workers seated directly next to a window opened them on a daily basis. The amount the windows were opened was dependent on the amount of wind. Workers not within an arm's reach of a window rarely opened windows at all.

The second question asked workers to evaluate their views of natural ventilation. The positive comments focused on the availability of fresh air. Some workers noted that breezes invigorated them, with the result of making them more active and productive. The majority of negative comments centered on the displacement of papers during higher wind gusts. Those workers note that the use of paperweights has alleviated the problem. One worker noted that bringing in fresh air with pollen aggravated her allergies.

Workers were specifically asked to qualitatively rate the effect of natural ventilation on their productivity. The majority of workers noted that natural ventilation does enhance their productivity. One person noted that natural ventilation was a desired feature, but wasn't sure if it had any impact on her productivity. Another person noted that she couldn't tell when natural ventilation was in use over air-conditioning. In some ways, this indicates that the system is operating in a seamless fashion as was intended. Finally, one person noted that productivity was decreased when natural ventilation is used too long on very humid days.

When asked to compare natural ventilation to air-conditioning, natural ventilation was hands-down favored. Some workers described air-conditioning as being too cold, too impersonal, or too dry. A few workers commented that air-conditioning required too much re-circulated air. Workers appeared to like having a connection to the external environment through the use of windows. One worker noted that air-conditioning gave her headaches. She noted that this occurred when moving in and out of the building during some of the hotter days of the summer.

In order to calibrate the thermal comfort model, workers were asked to evaluate their clothing type. During the summer, most occupants wear short-sleeved shirts with slacks or short dresses. During the fall and spring, workers wear long-sleeved shirts. During the winter, workers wear several layers for maximum flexibility.

Workers were asked to create their own definition of thermal comfort and estimate a range of temperatures that they are comfortable at during the summer. For some people, thermal comfort was defined as being in a state where you aren't even aware of the temperature or humidity. Others went on to further define thermal comfort as being able to focus on work. The range of temperatures given by workers was surprising. Most stated a range of 68 to 72°F. It is possible that these values were given because the survey was taken during late fall. One worker did specify ranges for both winter (68-72°F) and summer (74-76°F).

Lastly, workers were asked to comment on the building environment, in general. The main complaint was excessive glare from the sun. There were also some comments on odors and noise. Odors were from another worker's perfume or food. The noise was due to construction on a new dock at the building site. One worker also noted that the white noise generators used to mask sound were too noisy. It is possible that the actual source of the excessive noise was from ventilation fans. On site visits, it was noted that the mechanical system has a fairly high constant noise level.

7.8.3 Thermal Comfort Discussion

We have seen that occupants maintain an interior temperature within a 4 to 5°C band during natural ventilation use, even though the outdoor temperature varies within a band of 15°C. In section 6.3.5, we saw the use of an optimum comfort temperature. There has been much discussion over whether the comfort temperature can be applied to mixed-mode buildings, such as the Philip Merrill Environmental Center [de Dear & Brager, 2002]. Expectations of occupants in the center are likely higher than at Broadmoor, because of the availability of air-conditioning. Whenever the interior temperature rose above 78°F (25.6°C), air-conditioning was turned on. When we do compare the average indoor temperature to the comfort temperature, we see that there is less than 10% difference for 90% of the data. What remains to be seen is the performance of the comfort temperature at indoor temperatures higher than 78°F, since most of the revisions to thermal comfort standards are meant to address times when interior dry bulb temperatures may be higher than 78°F, due to natural ventilation use.

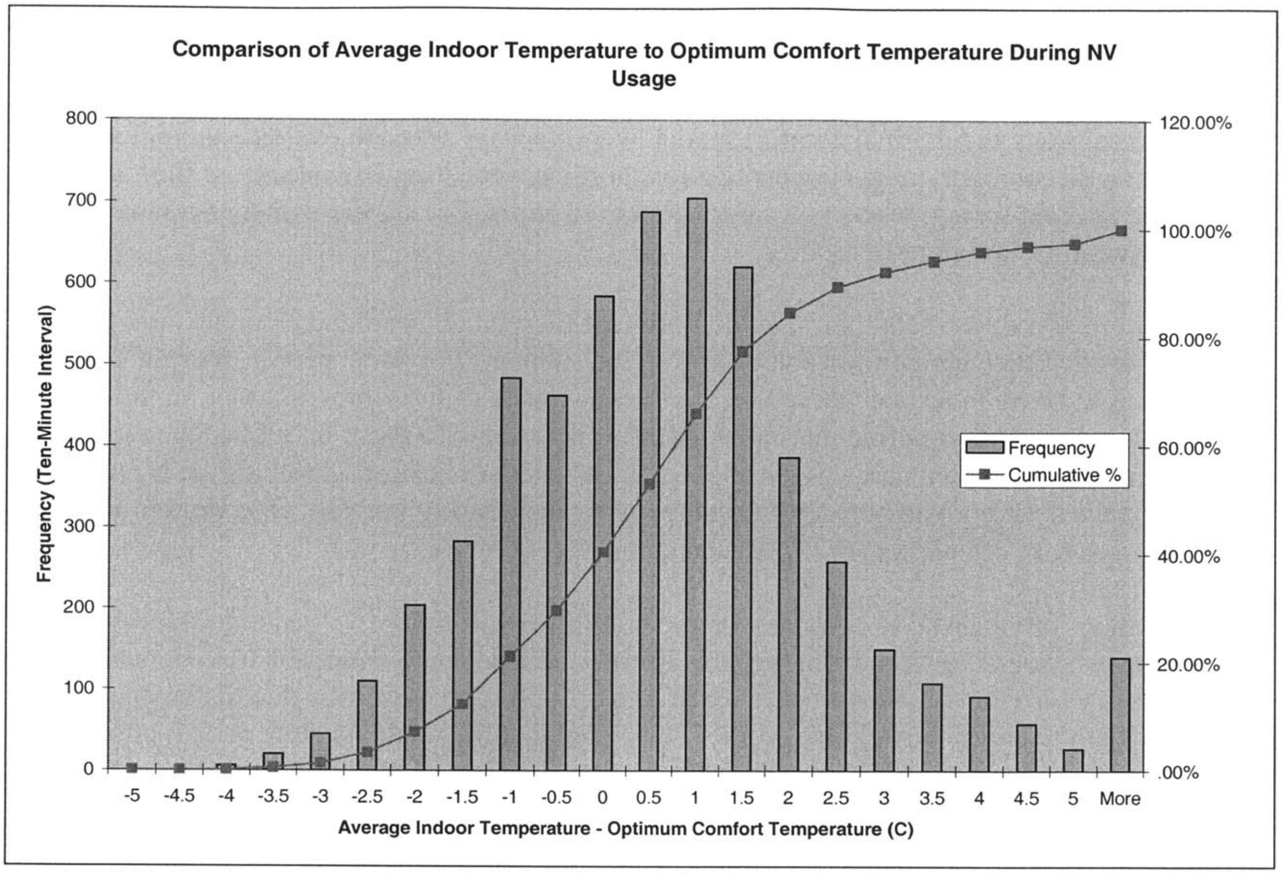


Figure 246 Comparison of average indoor temperature to optimum comfort temperature during occupied hours natural ventilation usage between May 16 and December 20, 2001.

7.9 Thermal Model

It was envisioned that a single-zone thermal model would be inadequate to accurately predict space temperatures in a building like the Philip Merrill Environmental Center. The reason for this conjecture is that the building consists of two levels that are open to each other. The airflow patterns in the building are also not as straightforward as at Broadmoor, since there are openings on all four sides of the buildings at 3 different heights. In reality, the model *appears* to fare quite well. From the plots below, we see that the model is generally able to predict the interior space temperature. It is hard to say with certainty if the results are conclusive though. On September 20th 2002, the agreement was not as good as on October 11th, 2002. The most probable reason for this is that different combinations of windows were opened on each day. This is also coupled with variability in predominant wind direction.

The airflow model used assumes an average windward pressure coefficient and an average leeward pressure coefficient. We also assume the internal heat load is equal to the total internal sensible heat load calculated in Table 29. The heat load due to solar radiation is calculated using the model described in the modeling chapter. We assume that the south side is shaded from direct radiation, while all other facades receive both direct and diffuse components of radiation. Conduction through the window and walls is calculated using a standard steady-state method.

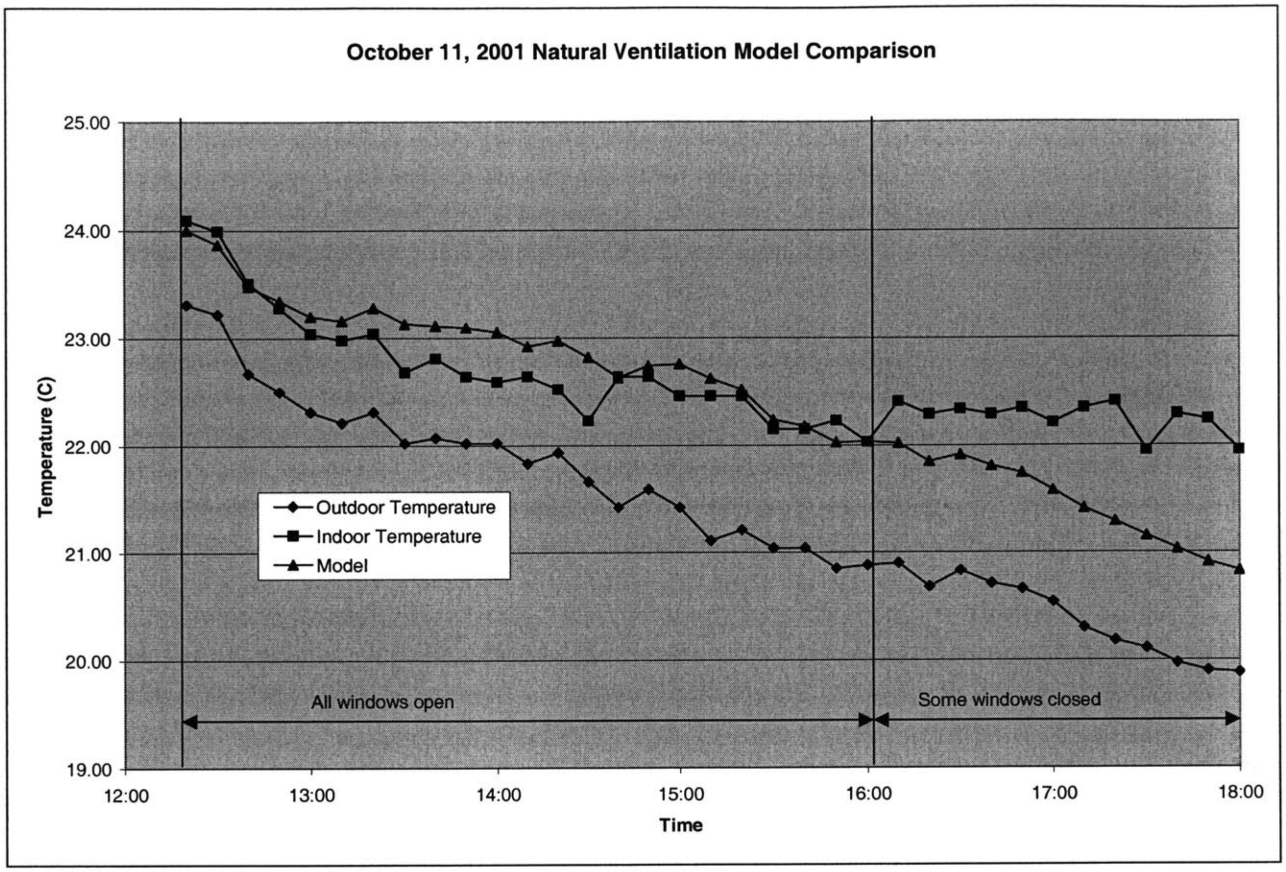


Figure 247 Comparison between indoor temperature predicted by model and actual indoor temperature, on October 11, 2001. The average wind direction was 199 degrees with an average speed of 6.6 m/s.

On October 11, 2001, the rate in change in indoor temperature matched the rate of change in outdoor temperature. The model was able to predict this rate of change fairly reasonably with no more than 5% difference in the actual temperature. At 4 pm, some windows in the building were closed, as indicated in Figure 247. The model continued to predict the same rate of change, while the indoor temperature appeared to level out.

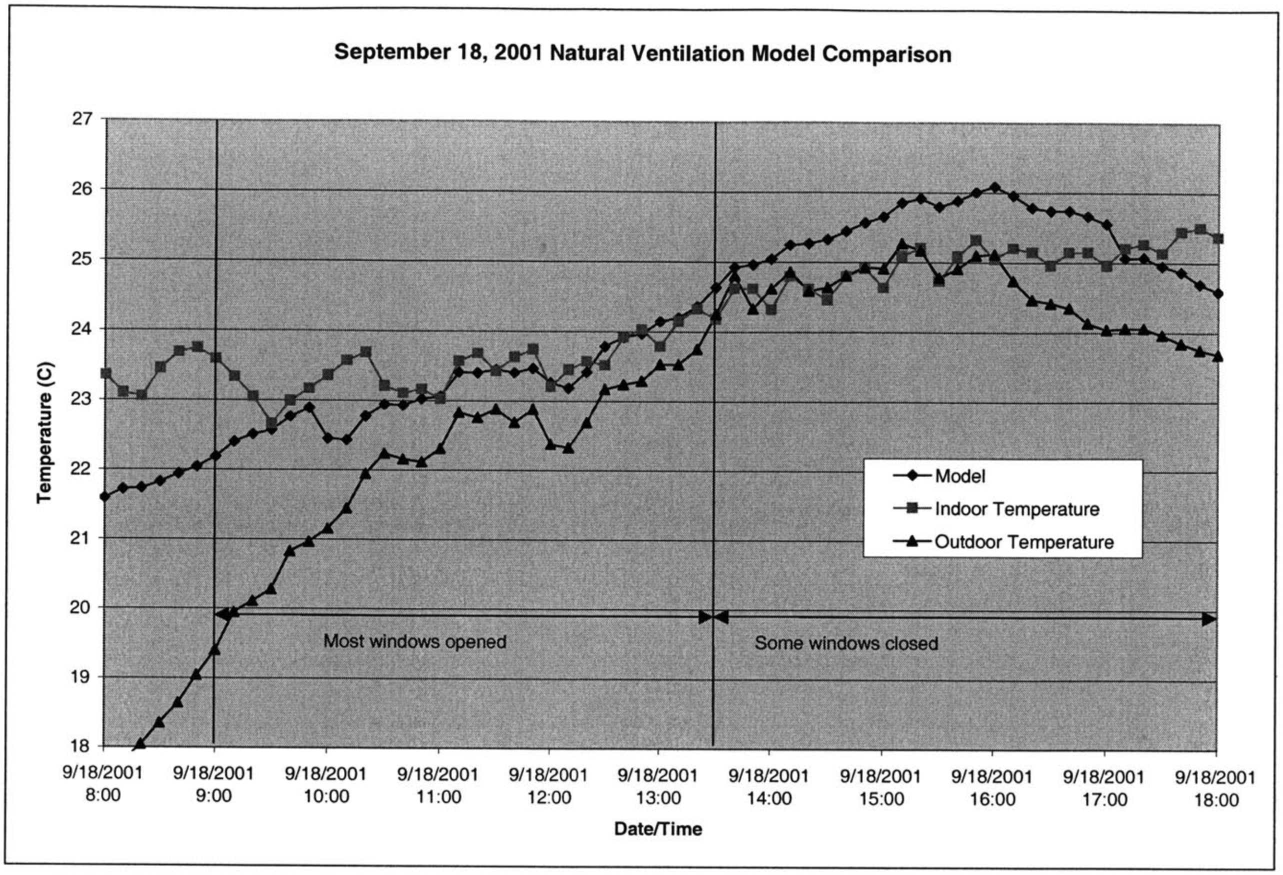


Figure 248 Comparison between indoor temperature predicted by model and actual indoor temperature, on September 18, 2001. Average wind direction was 223 degrees (from the southwest) with a wind speed average of 2.3 m/s.

On September 18, 2001, the rate in change in indoor temperature followed the rate in change in outdoor temperature. The model was able to predict the change in indoor temperature fairly well, with no more than 5% error. When some windows were closed at 3:30 pm, the model deviated more from the actual collected data. The actual indoor temperature moved closer to the outdoor temperature, an indication of the effect of higher wind speeds, even with fewer windows open.

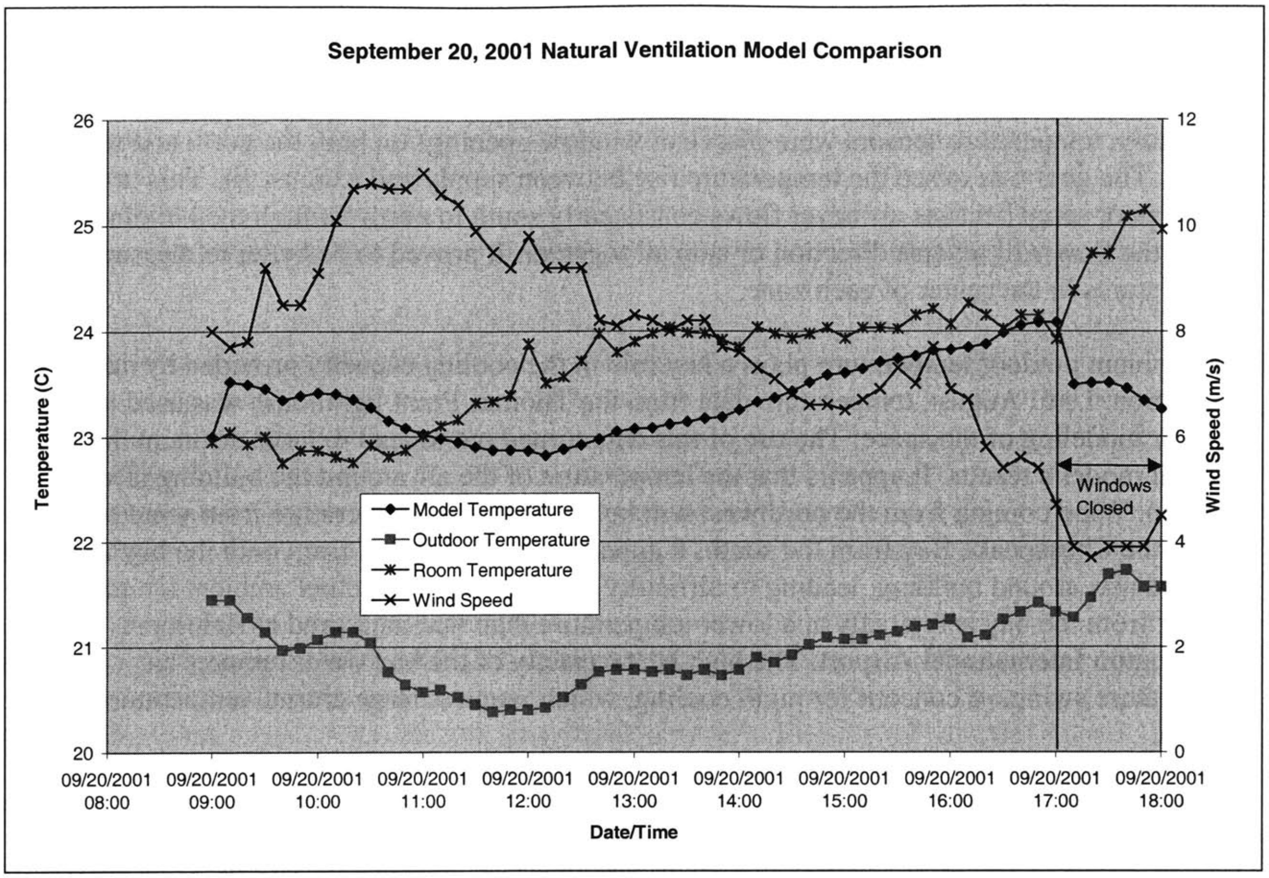


Figure 249 Comparison between indoor temperature predicted by model and actual indoor temperature, on September 20, 2001. The average wind direction was 176 degrees (from the south).

On September 20, 2001, the model was not able to follow the rate in change in indoor temperature as well as in the previous two cases discussed. The likely reason for this is the large change in wind speed between the morning and afternoon hours. That said, the overall error is still less than 5%.

When natural ventilation is used, there is a clear pattern to the behavior of the indoor temperature. Typically, if natural ventilation is used correctly, the indoor temperature will follow the same profile as the outdoor temperature, with a magnitude shift, depending on the strength of the wind outside. If the interior of the building featured more thermal mass, we would expect the indoor temperature to lag behind the outdoor temperature.

7.10 Monitoring Issues

Monitoring window operation was the greatest challenge in this research project. There are approximately 40 individually operated windows in the building. Knowing when and how much each window is open is a significant challenge. Typically, the building manager opens the windows along the south façade to 100%, when natural ventilation is first indicated for use for a particular day. If it gets too drafty, occupants located close to the windows will shut them. On the remaining facades, it appears that windows were not opened very often. If they were, they were only opened out to about 25% of their maximum capability. The wireless camera monitoring system that was installed helped verify when natural ventilation was used. Its use in seeing how far windows were open was a challenge, due to the low resolution of the cameras.

Originally, temperature sensors were placed at window openings on both the north and south façade. The goal was to see the temperature rise between supply and exhaust air. This turned out to be a poor setup because air never flows consistently south to north through the building. Often, the flow will reverse direction or stop all together. It proved to be better to measure temperatures in the center of each zone.

The ambient outdoor temperature plays a key role in the cooling capacity provided by natural ventilation. Until August, temperature data from the Thomas Point lighthouse was used in heat transfer modeling of the space. The use of this data turned out to lead to large errors in the thermal model's results. It appears that the temperature of the air around the building is *not* uniform. Wind coming from the northwest will be at a different temperature from wind coming across the Chesapeake Bay from the south. It appears that air streams from both the bay and from the land mix around building, leading to difficulty in measuring the actual ambient temperature. The air from the bay is typically at a lower temperature than that measured at Baltimore-Washington International Airport. The high heat capacity of the bay water tempers air temperature swings, a concern for night cooling, which requires large diurnal temperature swings.

7.11 Recommendations and Observations

The occupants in the building enjoy having an abundance of natural daylighting. They also enjoy the availability of natural ventilation, but are perhaps not aware of what is necessary to make it perform optimally. What has happened is that most workers do not play an active role in the control of the windows. For natural ventilation to work optimally, there are several considerations.

The building was sited to take advantage of south to north breezes. Often, the days when temperatures were within an optimal range for natural ventilation usage, the wind comes from the northwest. In the original analysis for natural ventilation, it appears that average temperature, humidity, and wind speed and direction values were used. This may provide general knowledge of when natural ventilation can be used, but it may hide intricacies in weather conditions. It is important that climate studies focus on hourly *daytime* temperatures and wind patterns coupled together.

When wind is coming from the west or east, it is essential that windows on those respective façades be open. This was not often the case. What would be optimal is for the building manager to check the direction of prevailing winds and notify workers to open windows on specific sides of the building. The notification can be done through email or using a whiteboard located in the entrance lobby.

Although internal heat loads for the building are typical for a commercial office building, the original usage ranges for natural ventilation of 68 to 77°F and 20 to 60% relative humidity turned out to be too high. It would be optimal is to design the natural ventilation system more like a conventional HVAC system based on the sensible heat ratio (SHR). Typically, supply air from diffusers is supplied on the condition line around 15°C (59°F). The building manager has indeed shifted the lower limit of outdoor temperature for natural ventilation usage to 40°F (4.44°C). The great drawback with this is that people close to the windows will feel a draft that results in discomfort. While windows were originally placed to provide a breeze to occupants that would enhance personal evaporative cooling, their placement may also hinder the use of natural ventilation.

As mentioned before, those closest to the windows are those likely to feel discomfort due to draft. They are also the most likely to actually operate the windows. Unfortunately, those in the center or leeward side of the building require the windows open 100% to provide maximum airflow for cooling.

One set of clerestory windows was out of service for many months. These windows represent an essential component of stack ventilation for the building. One concern is that the life cycle of these motorized windows is being shortened due to a bug in the building management software. After the system was reprogrammed in August of 2001, the clerestory windows would sometimes open and close every five to ten minutes; sometimes they stayed open when air-conditioning was running. Such erratic operation will confuse occupants and cause them to ignore the natural ventilation signs, just like false fire alarms eventually desensitize people to the need to evacuate quickly in the event of a real emergency.

The lighted open window signs are not enough to notify people to open windows. Because of the height of the cubicles, each worker has to physically be standing and looking at one of the signs to see its status. There can be up to an hour delay from when the signs light up to when windows are actually opened. This lag significantly reduces the potential of natural ventilation to work, given the internal heat loads. A suggestion is to use the paging system to notify workers of the system's status. The front desk should be able to tell the status of the system easily to make such announcements.

As of November 2001, if one or two people complain that it is too cold or too hot in the building, natural ventilation is turned off. This standard should be readjusted, considering that 100% satisfaction is often very difficult to achieve, even in an air-conditioned environment. An experiment to run is to use natural ventilation an entire day, as long as outdoor temperatures are below the current air-conditioning setpoint of 75°F, and ask *all* workers to rate their thermal sensation hourly. This experiment can allow the building manager to see the individual preferences of all the workers in the building. This is feasible since there are typically less than 75 people in the building at any one time and not thousands like in some larger office buildings.

Lighting represents a significant heat load in the building. On some site visits, lighting on the second floor was on when it appears to be unnecessary. The external shading appears to be working well, although for brief periods during the mornings, there is significant glare-causing direct sunlight. It was common to see people using ad hoc cardboard shields to block sunlight, during the first months of the building's operation. Internal aluminum blinds have since been installed, eliminating most glare from the sun.

The open walkway along the south façade presents a significant HVAC design challenge. During the winter, it was difficult to keep the lower space from getting too cold and the upper space from getting too hot. One design problem is that the upper windows on the south façade are parallel with the balcony wall. While this increases turbulence that can enhance the cooling effect, it also reduces the overall airflow velocity through the upper space. While a designer envisions that air will move according to simple geometrical boundary conditions, buoyancy forces add complication so that the air behaves adversely to the intended ventilation strategy.

The total area of the north windows was sized larger than that of the south windows to enhance airflow. The windows used to achieve this may not have been optimal due to the limited amount the north windows can open. The *effective* area of the south windows appears larger than that of the north windows. An alternative would have been to have large fixed windows on the north façade for daylighting, coupled with awning windows, similar to those used on the south façade, below them for ventilation. This recommendation is given from a qualitative standpoint and may have to be confirmed with computational fluid dynamic modeling.

The location of the two natural ventilation assist fans should be reversed. The upper floor requires more ventilation capacity than the more isolated section of the first floor. The damper on the upper floor fan does not open fully on its own, which is the major impediment to cooling, since it represents approximately 20% of the average airflow generated by having windows open. The lower level fan was typically shut-off in September and October of 2001 because it was leading to over-ventilation of the space.

In general, the coolest section of the building was the west side of the first floor. One major reason for this is the shading provided by the conference center. It blocks direct sun during the morning hours when natural ventilation would typically be used. Typically, the first floor remained 2°C cooler than the second floor. This is dependent on the actual ventilation rate for each floor. The temperatures between the west and east portions of the second floor were up to 1°C apart, depending on which windows were open, but are in general similar. Effectively, there are three zones to the building: two first floor zones, and the second floor as a whole.

In summary, natural ventilation works, but better control of the system, coupled with a more thermally massive structure, would extend the possible natural ventilation usage period. Even with more thermal mass though, intensive night cooling cannot be used, as is, due to security and rain issues. In the original design of the building, motorization of all windows was discussed, but not implemented due to cost. The motorized clerestory windows may be left open overnight in the future, once a rain sensor is installed. This may not be enough for effective night cooling though, due to relatively low achievable air change rates.

The thermal comfort analysis shows that occupants are comfortable when natural ventilation is used. What is perhaps unknown is how well occupants would respond to natural ventilation usage at higher indoor temperatures. The building manager should consider using natural ventilation at higher outdoor temperatures with all windows in the building open. As noted before, the combined use of natural ventilation with air-conditioning, for a mixed-mode system, likely causes occupants to have higher environmental expectations than occupants in wholly naturally ventilated buildings. This is a topic for future exploration and research.

Chapter 8 Conclusion and Recommendations

The case studies presented in this research show that natural ventilation can be harnessed effectively in the United States. Moreover, it has been shown that the buildings studied operate effectively even during periods of high heat and humidity. At the Broadmoor Wildlife Sanctuary's nature center, occupants have been happy with their work environment for almost two decades, even without the availability of active mechanical cooling. At Broadmoor, occupants have adapted and adjusted to weather conditions. On the hottest days, occupants move to a thermally massive lower level space or take advantage of personal desk fans. We see that when people are forced to adapt to a changing environment, they will often do so successfully.

At the Phillip Merrill Environmental Center, we see that natural ventilation can be used as a predominant ventilation strategy, with air-conditioning available to assist when necessary. Occupants at the Philip Merrill Center expressed content with natural ventilation, both through written and oral surveys and daily ratings of their thermal sensations. Since monitoring was performed during the building's first year of operation, many bugs in the building control system were found. Operation over the second year will likely be much better.

We found that simplicity should rule over automation when possible. In fact, occupants were seen to operate manual windows in a fashion that maintained fairly stable temperatures within the building. A lesson learned in the design of the Phillip Merrill Center is the need to do preliminary thermal and airflow modeling before windows are sized and placed. The internal and external heat loads on the building turned out to be higher than expected, forcing the acceptable operating temperature ranges to shift downwards. When this happened, the placement of some windows became inappropriate due to increased draft risk. There were also periods when air-conditioning had to be used because winds did not come from the predominant wind direction found in *macro* wind analysis. It would have been more effective to look at various wind scenarios, in an effort to create a building insensitive to wind direction.

For natural ventilation to gain a foothold in building design, architects and engineers should learn from the examples set by these two buildings, as well as buildings in Europe. Natural ventilation shows great promise for use in non-residential buildings in the United States, but designers must make the effort to keep natural ventilation in their repertoire and be persistent throughout the entire building commissioning process. It will take time for government regulations, fire codes, and ventilation and thermal comfort standards to change to make natural ventilation easier to implement, but until then, the buildings discussed in this research should give motivation that it can be done.

This project was initially focused on validating a simple thermal-fluids model. When it became clear that without the use of on-site tracer gas equipment, it would be difficult to do a full-scale validation study, the project moved towards looking at thermal comfort also. For future studies, a project should focus on either just model validation or thermal comfort, if personnel and equipment resources are limited. The reasoning behind this is to gain very conclusive data. While the thermal comfort surveying and model validation performed provide very interesting information, there are still some uncertainties. For the model, measurement of air change rate and solar radiation would have helped with model validation significantly. There would still be the issue of how to monitor windows though. What appears better than monthly visits is to remain on-site for a two-week period to monitor window operation, with the help of at least one assistant. If this is not possible, testing of the model on a mockup building would work for more control, although this has been done before in European natural ventilation projects and would not provide any insight into how occupants actually operate a system in a real world situation.

For the thermal comfort study, participation by all members of the building population, coupled with more instrumentation, such as more than one temperature measurement in each zone, would have made statistical uncertainty less of an issue. A move to a web-based thermal comfort survey might be easier for occupants to use. A web-based form would ensure that an accurate time-stamp goes along with the collected data. In this research, thermal sensation data was matched up with the average temperature over a particular morning or afternoon period. This correlates to occupants being asked to evaluate their overall thermal sensation for a corresponding morning or afternoon period. Since the use of natural ventilation results in a space temperature that is always changing, lumping together the temperatures during a 4-hour period may mask some of the intricacies associated with thermal comfort in a naturally ventilated building. In the future, occupants should be asked to rate their thermal sensation each hour at maximum. The difficulty with this is getting occupants to remember to do this, in the first place. The demands of work would prevent most people from doing this on a consistent basis.

The single-zone airflow and thermal model shows good agreement with actual experimental data collected at the Broadmoor Wildlife Sanctuary's nature center. The error is typically less than 5%, with no more than 10% error. The model also showed good agreement with the data collected at the Phillip Merrill Environmental Center, with errors less than 10%. The results were not as conclusive for this larger building, given that natural ventilation was typically only used a maximum of eight hours at a time; a weekly trend showing the effect of thermal mass was not possible. An energy analysis showed that using natural ventilation full-time from May to December of 2001 would save tens of thousands of kilowatt-hours of energy usage, not even including fan or pump energy.

In summary, focusing on a more specific aspect of naturally ventilated buildings can enhance future research. What is clear from this research project is that natural ventilation shows significant promise. The positives of natural ventilation appear to be improved productivity of workers, combined with lower energy consumption. The main point to consider with natural ventilation appears to be how to control it to provide optimal indoor environmental conditions with a wide range of outdoor conditions. For commercial buildings in the eastern United States, a mixed-mode system like the one at the Phillip Merrill Environmental Center appears to show the most promise for acceptability and adoption by the public, as well as those that design buildings and are concerned about current thermal comfort and ventilation standards.

Appendix A: MATLAB Code

A.1 Broadmoor Wildlife Sanctuary Scripts

A.1.1 Thermal Model

All values are in standard SI units of kilograms, meters, and seconds, unless otherwise noted. MATLAB was chosen as a development program because of its easy to use coding structures and syntax. These programs can be easily adjusted to other buildings, as long as the building's properties are available.

```
%Fixed Thermal Properties
cp = 1005 %heat capacity of air
hconv = 7 %convection from mass to air
cmass = 1000 %heat capacity of mass

%Variable Thermal Properties
rho = 1.2 %density of air
rhomass = 800 %density of mass

%Variable Condition Properties
aconv = 602 %area of surface heat transfer between room air and thermal mass
roomvol = 530 %volume of room
massvol = 30 %volume of thermal mass
time = 600 %time step
extarea = 204 %exterior surface area
resist = 0.189 %envelope heat transfer factor
swall = 65 %south wall area
ewall = 37.16 %east wall area
nwall = 65 %north wall area
wwall = 37.16 %west wall area
fenarea = 15 %window area
winresist = 2.73 %window heat transfer factor

%Input Text File
%datetime = date/time
%tout = ambient outdoor temperature
%wspd = wind speed
%wdir = wind direction
%hload = internal load
%sol = fenestration solar load
%wsol = wall solar load (S,E,N,W)
%roof = roof solar load
%window = window configuration
%sky = cloud cover
%test = experimental value
%base = basement temp
[dtime,tout,wspd,wdir,hload,sol,wsols,wsole,wsoln,wsolw,roof,window,sky,test,
base]=textread('input.txt','%16c %f %f %f %f %f %f %f %f %f %f %f %f %f %f');

%index variables
i = 1
```

```
%Variables of Interest
tmassinit = 25 %initial mass temp at time 0
troominit = 25 %initial room temp at time 0

tmass(i)=(tmassinit-troominit)*exp(hconv*aconv*time/(rhomass*massvol*cmass))+
         troominit;
troom(1)= troominit;

i = 2

while i < length(tout)+1

%Ventilation Due to Wind
  if window(i) == 1
      %Full ventilation during day
      A1 = 0; %Top windward
      A2 = 2.3; %Bottom windward
      A3 = 0.16; %Top leeward (stack vent)
      A4 = 2.4; %Bottom leeward
   elseif window(i) == 0
      %Nighttime summer ventilation
      A1 = 0; %Top windward
      A2 = 1.2; %Bottom windward
      A3 = 0.16; %Top leeward
      A4 = 1.2; %Bottom leeward
   elseif window(i)==2
      %Window Ventilation only
      A1 = 0;
      A2 = 1.2;
      A3 = 0.16;
      A4 = 0.2;
   else
      %Infiltration only
      A1 = 0; %Top windward
      A2 = 0.2; %Bottom windward
      A3 = 0.16; %Top leeward
      A4 = 0.2; %Bottom leeward
   end

   H = 3; %Stack ventilation height
   Cd=0.64;

   %Wind Model
   if wdir(i)==270
      Cp1=0.4;
      Cp2=-0.3;
   elseif wdir(i)==292.5
      Cp1=0.3;
      Cp2=-0.4;
   elseif wdir(i)==315
      Cp1=0.2;
      Cp2=-0.5;
   elseif wdir(i)==337.5
      Cp1=-0.2;
      Cp2=-0.55;
   elseif wdir(i)==0
```

```
      Cp1=-0.6;
      Cp2=-0.6;
   elseif wdir(i)==22.5
      Cp1=-0.55;
      Cp2=-0.2;
   elseif wdir(i)==45
      Cp1=-0.5;
      Cp2=0.2;
   elseif wdir(i)==67.5
      Cp1=-0.4;
      Cp2=0.3;
   elseif wdir(i)==90
      Cp1=-0.3;
      Cp2=0.4;
   elseif wdir(i)==112.5
      Cp1=0.25;
      Cp2=-0.22;
   elseif wdir(i)==135
      Cp1=-0.5;
      Cp2=0.2;
   elseif wdir(i)==157.5
      Cp1=-0.55;
      Cp2=-0.2;
   elseif wdir(i)==180
      Cp1=-0.6;
      Cp2=-0.6;
   elseif wdir(i)==202.5
      Cp1=-0.2;
      Cp2=-0.55;
   elseif wdir(i)==225
      Cp1=0.2;
      Cp2=-0.5;
   elseif wdir(i)==247.5
      Cp1=0.3;
      Cp2=-0.4;
   end

   Aw = (1/(A1+A2)^2+1/(A3+A4)^2)^(-1/2);

   %Wind effect flow rate [m^3/s]
   Qw(i) = Cd*Aw*wspd(i-1)*abs(Cp1-Cp2)^(1/2);

   Ab = (1/(A1+A3)^2+1/(A2+A4)^2)^(-1/2);

   %Stack effect flow rate [m^3/s]
   Qb(i) = Cd*Ab*(4*abs(troom(i-1)-tout(i-1))*9.8*H/(tout(i-1)+
          troom(i-1)))^0.5;

   QN(i) = sqrt(Qb(i)^2+Qw(i)^2); %Combined Wind and Stack Effect

%Thermal

      %Solar-Air Temperature
      tsolS(i) = tout(i-1)+0.026*wsols(i-1)*1.15;
      tsolE(i) = tout(i-1)+0.026*wsole(i-1)*1.15;
      tsolN(i) = tout(i-1)+0.026*wsoln(i-1)*1.15;
      tsolW(i) = tout(i-1)+0.026*wsolw(i-1)*1.15;
```

```
       %Basement Mixing
       if window(i)==1
          mbase(i) = rho*Cd*0.05*(4*abs(troom(i-1)-base(i-1))*9.8*H/
                     (tout(i- 1)+base(i-1)))^0.5;
       else
          mbase(i) = 0;
       end

       if tout(i-1)>base(i-1)
          mbase(i) = -mbase(i)*cp*base(i);
       else
          mbase(i) = mbase(i)*cp*base(i);
       end

       %Window conduction
       wincond(i) = fenarea*winresist*(tout(i-1)-troom(i-1));

       %Combined conduction and radiation wall heat transfer
       wallsol(i) = swall*resist*(tsolS(i)-troom(i-1))+ewall*resist*(tsolE(i)-
                    troom(i-1))+nwall*resist*(tsolN(i)-
                    troom(i-1))+wwall*resist*(tsolW(i)-troom(i-1));

        %Conduction heat transfer from basement
        basecond(i) = 260*0.2*(base(i-1)-troom(i-1));
        mflow = QN(i)*rho;

        tmass(i) = (tmass(i-1)-troom(i-1))*
                   exp(hconv*aconv*time/(rhomass*massvol*cmass))+troom(i-1);

        steady = (wincond(i)+mbase(i)+basecond(i)+hload(i-1)+sky(i-1)*
                 sol(i-1)+sky(I-1)*wallsol(i)+mflow*cp*tout(i)+
                 hconv*aconv*tmass(i))/((rho*cp*roomvol)*
                 ((mflow/(rho*roomvol))+(hconv*aconv/(rho*cp*roomvol))));

        transient = (troom(i-1)-steady)*exp(-time*((mflow/(rho*roomvol))+
                    (hconv*aconv/(rho*cp*roomvol))));

        troom(i) = steady+transient;
        i=i+1;
end
```

A.1.2 Solar Radiation Model

```
%Start and End Date
sday = 180; %day of year
eday = 190;

%Variables
lat = 42.29*(pi/180);
long = 71.35*(pi/180);
sigma = [pi/2,pi/2,pi/2,pi/2,0]; %Surface Tilt
reflect = 0.2;
sc = 0.88;
psi = [0,-pi/2,pi,pi/2,0]; %(S,E,N,W,R);
```

```
%ABC Values
load abc.txt
A = abc(:,1);
B = abc(:,2);
C = abc(:,3);


%Building Shading
shade = [1 1 1 1 1]; %1 for no shade, 0 for shade, [S,E,N,W,R]


%Variables Dependent on Date
i = 1 %index for time interval
z = 144 % 144 ten minute increments
j = sday %day index counter
k = 1 %overall index counter
t = 1 %building side counter


while t<=5
   while j<=eday
      if i<=z
         %Julien Day (day of year)
         N = (j-1)*(360/365)*pi/180;

        %Equation of time (min)
         eot = 229.2*(0.000075+0.001868*cos(N)-0.032077*sin(N)-
               0.014615*cos(2*N)-0.04089*sin(2*N));

         %Time (min)
         time = 10*(i-1)+eot+4*(90-long*(180/pi));

         %Hour Angle
         H = 0.25*abs(720-time)*pi/180;

         %Declination
         delta = 0.39673-22.9132745*cos(N)+4.0254304*sin(N)-
                 0.3872050*cos(2*N)+0.05196728*sin(2*N)-0.1545267*cos(3*N)+
                 0.08479777*sin(3*N);

         %Solar Altitude
         beta = asin(cos(lat)*cos(H)*cos(delta*pi/180)+sin(lat)*
                sin(delta*pi/180));

         %Solar Azimuth
         phi = acos((sin(beta)*sin(lat)-sin(delta*pi/180))/
               (cos(beta)*cos(lat)));

         if i<=13
            phi = -phi;
         end

         %Surface-solar Azimuth
         gamma = phi-psi(t); %radians

         %Incident Angle
         theta = acos(cos(beta)*cos(gamma)*sin(sigma(t))+sin(beta)*
```

```
                 cos(sigma(t)));

         %Direct Normal Irradiance
         if exp(B(j)/sin(beta))==0
            edn=0;
         else
            edn=A(j)/exp(B(j)/sin(beta));
         end

         %Direct Irradiance
         eD = edn*cos(theta)*shade(t);

         if theta>90*pi/180
            eD = 0;
         end


         %Diffuse Radiation
         ed = C(j)*eD*((1+cos(sigma(t)))/2);

         %Reflected Radiation
         eR = (edn*sin(beta)+C(j)*edn)*reflect*(1-cos(sigma(t)))/2;

         %SHGF
         TSHGF = eD*(-0.00885+2.71235*cos(theta)-0.62062*(cos(theta))^2-
                 7.07329*(cos(theta))^3+9.75995*(cos(theta))^4-
                 3.89922*(cos(theta))^5)+2*ed*(-0.00885/2+2.71235/3-
                 0.62062/4-7.07329/5+9.75995/6-3.89922/7);

         ASHGF = eD*(0.01154+0.77674*cos(theta)-3.94657*(cos(theta))^2+
                 8.57811*(cos(theta))^3-8.38135*(cos(theta))^4+
                 3.01*(cos(theta))^5)+2*ed*(0.01154/2+0.77674/3-
                 3.94657/4+8.57811/5-8.38135/6+3.01188/7);

         SHG(k,t) = sc*TSHGF+sc*ASHGF*0.267;

         %Transmitted Component
         Diffuse(k,t) = ed;
         Etotal(k,t) = eD+ed+eR;
         if beta<=0
            Etotal(k,t)=0;
            SHG(k,t)=0;
         end
         k=k+1;
         i=i+1;
      else
      i=1;
         j=j+1;
      end
   end
   t=t+1;
   k=1;
   i=1;
   j=sday;
end
sarea = 6 %South fenestration area
earea = 0 %East fenestration area
```

```
narea = 5 %North fenestration area
warea = 4 %West fenestration area
area = [sarea earea narea warea]

for m=1:size(Etotal,1)
   Fengain(m) = SHG(m,1)*area(1)+SHG(m,2)*area(2)+SHG(m,3)*area(3)+SHG(m,4)*
   area(4);
end
Fengain = Fengain';
save Fengain.txt Fengain -ASCII %Fenestration solar gain
save Etotal.txt Etotal -ASCII %Solar load for walls
```

A.1.3 Energy Model

```
[Ta] = textread('temps.txt','%f'); %Read text file with exterior temperatures
Tin = 24;
WinUvalue = 2.73;
WallUvalue = 0.189;
WinArea = 15;
WallArea = 204.32;
FenGain = 4000;
InternalGain = 3000;
i=1;
Total=0;
while i<=length(Ta)
   Energy(i) = FenGain+InternalGain+WinUvalue*WinArea*
               (Ta(i)-Tin)+WallUvalue*WallArea*(Ta(i)-Tin);
   Total = Total+Energy(i);
   i = i+1;
end
Power = Total/i/1000*i/6;
Cost = Power*0.12;
```

A.2 Chesapeake Bay Foundation Scripts

A.2.1 Thermal Model

```
%Fixed Thermal Properties
cp = 1005; %heat capacity of air
hconv = 7; %convection from mass to air
cmass = 1000; %heat capacity of mass

%Variable Thermal Properties
rho = 1.2; %density of air
rhomass = 800; %density of mass

%Variable Condition Properties
aconv = 4000; %area of surface heat transfer between room air and thermal
mass
totalmass = 160000;
time = 600; %time step (seconds)
resist = 0.24; %envelope heat transfer factor
swall = 242.53; %All windows
ewall = 99.49;
nwall = 390.60;
wwall = 99.49;
```

```
fenarea = 685.43;
roomvol = 8331;

%Text Input
%datetime = date/time
%tout = ambient outdoor temperature
%wspd = wind speed
%wdir = wind direction
%hload = internal load
%sol = fenestration solar load
%wsol = wall SHGF (S,E,N,W)
%solroof = roof SHGF
%window = window configuration
%sky = cloud cover percentage
%test = experimental value
%fanvol = fan volume

[dtime,tout,wdir,wspd,hload,sol,wsols,wsole,wsoln,wsolw,solroof,window,sky,
test,fanvol] = textread('input.txt','%16c %f %f %f %f %f %f %f %f %f %f %f %f
%f %f');

%Index variables
i = 1

%Variables of interest
tmassinit = 23 %initial mass temp at time 0
%mass temp = troom
troominit = 23 %initial room temp at time 0
%room temp = tmass
tmass(i)=(tmassinit-troominit)*exp(-
hconv*aconv*time/(totalmass*cmass))+troominit;
troom(1)= troominit;

i = 2
while i < length(tout)+1

%Ventilation Due to Wind
   if window(i)==1
      A1 = 0; %Top windward
      A2 = 33.5744*.33; %Bottom windward
      (0.33 factor to correct for terrain change between weather station and
      the building)
      A3 = 24.54*.33; %Top leeward
      A4 = 15.62*.33; %Bottom leeward
   elseif window(i)==0
      A1 = 0.001; %Top windward
      A2 = 4*.33; %Bottom windward
      A3 = 24.54*.33; %Top leeward
      A4 = 0.001; %Bottom leeward
   else
      A1 = 0.001; %Top windward
      A2 = 3.71; %Bottom windward
      A3 = 15; %Top leeward
      A4 = 0.001; %Bottom leeward
   end

   H = 9; %Stack ventilation height
```

```
Cd = 0.64;

%Note that North is 0 degrees
if and(wdir(i)>=0,wdir(i)<=11.25)
   Cp1=0.5;
   Cp2=-0.7;
elseif and(wdir(i)>=11.25,wdir(i)<=33.75)
   Cp1=0.375;
   Cp2=-0.75;
elseif and(wdir(i)>=33.75,wdir(i)<=56.25)
   Cp1=0.25;
   Cp2=-0.8;
elseif and(wdir(i)>=56.25,wdir(i)<=78.75)
   Cp1=-0.125;
   Cp2=-0.65;
elseif and(wdir(i)>=78.75,wdir(i)<=101.25)
   Cp1=-.5;
   Cp2=-.5;
elseif and(wdir(i)>=101.25,wdir(i)<=123.75)
   Cp1=-.125;
   Cp2=-0.65;
elseif and(wdir(i)>=123.75,wdir(i)<=146.25)
   Cp1=0.25;
   Cp2=-0.8;
elseif and(wdir(i)>=146.25,wdir(i)<=168.75)
   Cp1=0.35;
   Cp2=-0.75;
elseif and(wdir(i)>=168.75,wdir(i)<=191.25)
   Cp1=0.5;
   Cp2=-0.7;
elseif and(wdir(i)>=191.25,wdir(i)<=213.75)
   Cp1=0.275;
   Cp2=-0.75;
elseif and(wdir(i)>=213.75,wdir(i)<=236.25)
   Cp1=0.2;
   Cp2=-0.8;
elseif and(wdir(i)>=236.25,wdir(i)<=258.75)
   Cp1=-.15;
   Cp2=-0.65;
elseif and(wdir(i)>=258.75,wdir(i)<=281.25)
   Cp1=-.5; %0.6
   Cp2=-.5; %-0.35
elseif and(wdir(i)>=281.25,wdir(i)<=303.75)
   Cp1=-.125;
   Cp2=-0.65;
elseif and(wdir(i)>=303.75,wdir(i)<=326.25)
   Cp1=0.25;
   Cp2=-0.8;
elseif and(wdir(i)>=326.25,wdir(i)<=348.75)
   Cp1=0.35;
   Cp2=-0.65;
elseif and(wdir(i)>=348.75,wdir(i)<=360)
   Cp1=0.5;
   Cp2=-0.7;
end

Aw(i) = (1/(A1+A2)^2+1/(A3+A4)^2)^(-1/2);
```

```
   %Wind effect flow rate [m^3/s]
   Qw(i) = Cd*Aw(i)*wspd(i-1)*sqrt(Cp1-Cp2);

   Ab = (1/(A1+A3)^2+1/(A2+A4)^2)^(-1/2);


   %Stack effect flow rate [m^3/s]
   Qb(i) = Cd*Ab*(4*abs(troom(i-1)-tout(i-1))*9.8*H/(tout(i-1)+
          troom(i-1)))^0.5;

   QN(i) = sqrt((Qw(i))^2+(Qb(i))^2); %Combined wind and stack effect

%Thermal

      %Solar
      tsolS(i) = tout(i-1)+0.026*wsols(i-1)*1.15;
      tsolE(i) = tout(i-1)+0.026*wsole(i-1)*1.15;
      tsolN(i) = tout(i-1)+0.026*wsoln(i-1)*1.15;
      tsolW(i) = tout(i-1)+0.026*wsolw(i-1)*1.15;


      %Combined conduction and radiation wall heat transfer
      wallsol(i) = swall*resist*(tsolS(i)-troom(i-1))+ewall*resist*(tsolE(i)-
                   troom(i-1))+nwall*resist*(tsolN(i)-troom(i-1))+
                   wwall*resist*(tsolW(i)-troom(i-1));

      mflow = QN(i)*rho+fanvol(i-1);

      wincond(i) = fenarea*3.54*(tout(i)-troom(i-1)); %Window Conduction

      tmass(i) = (tmass(i-1)-troom(i-1))*exp(-hconv*aconv*time/
                 (totalmass*cmass))+troom(i-1);

      steady = (sol(i-1)*sky(i-1)+wallsol(i)+wincond(i)+hload(i-1)+
               mflow*cp*tout(i)+hconv*aconv*tmass(i))/((rho*cp*roomvol)*
               ((mflow/(rho*roomvol))+(hconv*aconv/(rho*cp*roomvol))));

      transient = (troom(i-1)-steady)*exp(-time*((mflow/(rho*roomvol))+
                  (hconv*aconv/(rho*cp*roomvol))));

      troom(i) = steady+transient;
      i = i+1;
end
```

A.2.2 Solar Radiation Model

```
%Start and End Date
sday = 136;
eday = 365;

%Variables
lat = 38.9*(pi/180);
long = 76.4*(pi/180);
sigma = [pi/2,pi/2,pi/2,pi/2,0]; %Surface Tilt
reflect = 0.2;
```

```
sc = 0.88;
psi = [0,-pi/2,pi,pi/2,0]; %(S,E,N,W,R);

%ABC Value
load abc.txt
A = abc(:,1);
B = abc(:,2);
C = abc(:,3);

%Building Shading
shade = [0 1 1 1 1]; %1 for no shade, 0 for shade, [S,E,N,W,R]


%Variables Dependent on Date
i = 1 %index for time interval
z = 144 % 144 ten minute increments
j = sday %day index counter
k = 1 %overall index counter
t = 1 %building side counter

while t<=5
   while j<=eday
      if i<=z
         %Julien Day
         N = (j-1)*(360/365)*pi/180;

         %Equation of time
         eot = 229.2*(0.000075+0.001868*cos(N)-0.032077*sin(N)-
               0.014615*cos(2*N)-0.04089*sin(2*N));

         %Time
         time = 10*(i-1)+eot+4*(90-long*(180/pi));

         %Hour Angle
         H = 0.25*abs(720-time)*pi/180;

         %Declination
         delta = 0.39673-22.9132745*cos(N)+4.0254304*sin(N)-
                 0.3872050*cos(2*N)+0.05196728*sin(2*N)-0.1545267*cos(3*N)+
                 0.08479777*sin(3*N);

         %Solar Altitude
         beta = asin(cos(lat)*cos(H)*cos(delta*pi/180)+sin(lat)*
                sin(delta*pi/180));

         %Solar Azimuth
         phi = acos((sin(beta)*sin(lat)-sin(delta*pi/180))/
               (cos(beta)*cos(lat)));

         if i<=13
            phi = -phi;
         end

         %Surface-solar Azimuth
         gamma = phi-psi(t);

         %Incident Angle
```

```
            theta = acos(cos(beta)*cos(gamma)*sin(sigma(t))+sin(beta)*
                    cos(sigma(t)));

            %Direct Normal Irradiance
            if exp(B(j)/sin(beta))==0
               edn = 0;
            else
               edn = A(j)/exp(B(j)/sin(beta));
            end

            %Direct Irradiance
            eD = edn*cos(theta)*shade(t);

            if theta>90*pi/180
               eD = 0;
            end

            %Diffuse Radiation
            ed = C(j)*eD*((1+cos(sigma(t)))/2);

            %Reflected Radiation
            eR = (edn*sin(beta)+C(j)*edn)*reflect*(1-cos(sigma(t)))/2;

            %SHGF
            TSHGF = eD*(-0.00885+2.71235*cos(theta)-0.62062*(cos(theta))^2-
                    7.07329*(cos(theta))^3+9.75995*(cos(theta))^4-
                    3.89922*(cos(theta))^5)+2*ed*(-0.00885/2+2.71235/3-
                    0.62062/4-7.07329/5+9.75995/6-3.89922/7);

            ASHGF = eD*(0.01154+0.77674*cos(theta)-3.94657*(cos(theta))^2+
                    8.57811*(cos(theta))^3-8.38135*(cos(theta))^4+
                    3.01*(cos(theta))^5)+2*ed*(0.01154/2+0.77674/3-3.94657/4+
                    8.57811/5-8.38135/6+3.01188/7);

            SHG(k,t) = sc*TSHGF+sc*ASHGF*0.267;

            %Transmitted Component
            Diffuse(k,t) = ed;
            Etotal(k,t) = eD+ed+eR;
            if beta<=0
               Etotal(k,t) = 0;
               SHG(k,t) = 0;
            end
            k = k+1;
            I = i+1;
         else
         i = 1;
            j = j+1;
         end
      end
      t = t+1;
      k = 1;
      i = 1;
      j = sday;
   end
   sarea = 514.5 %South fenestration area
   earea = 24.83 %East fenestration area
```

```
narea = 121.23 %North fenestration area
warea = 24.83 %West fenestration area
area = [sarea earea narea warea]

for m = 1:size(Etotal,1)
   Fengain(m) = SHG(m,1)*area(1)+SHG(m,2)*area(2)+SHG(m,3)*area(3)+SHG(m,4)*
                area(4);
end
Fengain = Fengain';
save Fengain.txt Fengain -ASCII %Fenestration solar gain
save Etotal.txt Etotal -ASCII %Solar load for walls
```

A.2.3 Energy Model

```
[Ta] = textread('temps.txt','%f'); %Read text file with outdoor temperatures.
Tin = 24;
WinUvalue = 3.54;
WallUvalue = 0.24;
WinArea = 685.43;
WallArea = 832.11;
FenGain = 20000;
InternalGain = 32000;
i = 1;
Total = 0;
while i<=length(Ta)
   Energy(i) = FenGain+InternalGain+WinUvalue*WinArea*
               (Ta(i)-Tin)+WallUvalue*WallArea*(Ta(i)-Tin);
   if Energy(i)<0
      Energy(i) = 0;
   end
   Total = Total+Energy(i);
   i = i+1;
end
Power = Total/i/1000*i/6;
Cost = Power*0.12;
```

Appendix B: Experimental Data

There is too much data to include with this document. Instead, the data has been placed on an MIT web server (http://naturalvent.mit.edu/thesis/). The format of the data is provided in the following tables:

Data Point	**Comments**
Date/Time	Time is in 24-hour format
Outside Temperature [°C]	On-site weather station and outdoor HOBO
Wind Speed [m/s]	On-site weather station, averaged over 10-minute intervals
Wind Direction [°]	0° = North , averaged over 10-minute intervals
Relative Humidity [%]	Indoor and outdoor
Basement [°C]	Indoor HOBO
Lobby [°C]	Indoor HOBO
Office [°C]	Indoor HOBO
Assembly Room [°C]	Indoor HOBO
Stack Vent [°C]	Indoor HOBO
Attic [°C]	Indoor HOBO
Window	West window status [1.0 = open]
Door	East door status [1.0 = open]

Table 35 Description of Broadmoor data files.

Data Point	**Comments**
Date/Time	Time is in 24-hour format
Outside Temperature [°C]	Outdoor HOBO
Wind Speed [m/s]	Thomas Point Lighthouse, averaged over 10-min. intervals
Wind Direction [°]	0° = North, averaged over 10-min. intervals
Relative Humidity [%]	Indoor HOBO
1W [°C]	Indoor HOBO
1E [°C]	Indoor HOBO
1E Fan [°C]	Indoor HOBO
2W [°C]	Indoor HOBO
2E [°C]	Indoor HOBO
2E Fan [°C]	Indoor HOBO
2E High [°C]	Indoor HOBO
Atrium [°C]	Indoor HOBO
Window	HOBO state loggers [1.0 = open]
System	Building management system [1.0 = NV on]
Wireless	Camera monitoring [1.0 = windows open]

Table 36 Description of Chesapeake Bay Foundation data files.

Due to changes in instrumentation at various times, some data points may not be available for all data sets.

Appendix C: On-Site Visit Data

A total of eleven site visits to the Philip Merrill Building were made. A total of twelve site visits to the Broadmoor Sanctuary were made. Each visit consisted of brief interviews with building staff, downloading of data from HOBO loggers, installation or movement of equipment, and handheld measurements of air velocity and temperature.

Date	Data Download	Equipment Installation	Interview	Handheld Measurement
April, 24, 2001		✓	✓	
June 12, 2001	✓	✓	✓	✓
June 20, 2001	✓		✓	
June 30, 2001	✓	✓	✓	✓
July 27, 2001	✓		✓	✓
August 3, 2001	✓	✓	✓	✓
August 16, 2001	✓		✓	✓
August 24, 2001	✓	✓	✓	✓
September 11, 2001	✓		✓	✓
September 27, 2001	✓		✓	✓
October 23, 2001	✓		✓	
December 18, 2001	✓		✓	

Table 37 Summary of Broadmoor site visits.

Date	Data Download	Equipment Installation	Interview	Handheld Measurement
November 23, 2000				
March 23, 2001		✓	✓	✓
June 1, 2001	✓			✓
July 9, 2001	✓		✓	✓
July 12, 2001	✓			✓
August 8, 2001	✓			
August 10, 2001	✓		✓	
September 17, 2001	✓		✓	✓
October 11, 2001	✓			✓
October 12, 2001	✓		✓	✓
November 20, 2001	✓		✓	
December 31, 2001	✓			

Table 38 Summary of Chesapeake Bay Foundation site visits.

C.1 Broadmoor Visit Summaries

C.1.1 April 24, 2001

After discussions with Gerard Ives, the architect of the nature center, a site visit was arranged. A meeting with Elissa Landre, head of the Broadmoor Sanctuary, took place. Sensors were subsequently installed in seven locations. As of this point, an on-site weather station was not installed.

C.1.2 June 12, 2001

Data from all loggers was downloaded. The louvered doors were opened for full-time ventilation in early May. Measurements of vents and windows were taken. Surface temperature data was taken. The weather station was installed off a wall on the west façade.

Location	**Time**	**N**	**E**	**S**	**W**	**Ceiling**	**Floor**
Assembly Room	12:50	22 °C	21.8	22	22.1	22.4	22.1
Closed Office	12:55	23.1	23	24	23.1	23.9	23.1
Conference Room	13:00	22.6	22.6	22.6	23.2	23.4	22.2
Basement	13:05	21.7	22.6	21.5	20.8	21.8	19.8
Outside Walls	13:10	26.5	22.3	24.8	25.2	NA	20.6

Table 39 Broadmoor surface temperature readings for June 12, 2001.

C.1.3 June 20, 2001

Data from all loggers was downloaded.

C.1.4 June 30, 2001

Data from all loggers was downloaded. It was found that data from the weather station was reading much lower than values recorded at Boston's Logan International Airport, as well as Worcester's Regional Airport. The wind station was subsequently moved out into the field west of the building.

Location	**Time**	**Air Velocity (m/s)**
West door	14:45	1.0, 0.8, 0.87, 1.98, 0.98
West window	14:48	1.37, 1.06, 1.48, 1.43, 1.72
East right door	14:50	0.7, 0.91, 0.84
East left door	14:54	0.64, 0.63, 0.69
Desk Fan 1	NA	0.82
Desk Fan 2	NA	0.84
East right door	14:58	0.94, 1.17
Stack	15:00	0.68, 0.58, 0.62, 0.72, 1.03, 0.95

Table 40 Broadmoor air velocity readings for June 30, 2001.

Location	Time	N	E	S	W	Ceiling	Floor
Lobby Area	15:55	30.7	30.7	32.7	30.9	30.4	29.2
Assembly Room	15:56	29.1	28.8	28.4	28.6	28.6	27.9
Closed Office	15:57	29.6	29.3	29.3	29.3	29.8	28.1
Conference Room	15:58	29.3	30.2	29.8	29.3	29.2	27.8
Basement	15:59	23.6	24.4	24.2	23	23.6	22.6
Staircase	16:00	24	24.1	25.1	23.8	24.8	23.6
Sunspace	16:05	45.4	NA	NA	NA	NA	48.9

Table 41 Broadmoor surface temperature readings for June 30, 2001.

C.1.5 July 27, 2001

Data from all loggers was downloaded. A tracer gas experiment was run using grab bottle sampling techniques.

Tracer Gas Experiment One

Window Operation: West and east louvered doors (80" x 35") and 2 west windows (30" x 26") open.

Stack: Staircase down. Effective opening area (53" x 24")

Weather: Clear sky

Occupancy: One lobby desk worker. Two full-time workers on main floor. One full-time worker on ground floor. Several campers in and out of the building during five hour monitoring period. Approximately 15 visitors with visit length of five minutes (to use bathroom and pay admission fees).

Location: Assembly Room

Time	Operation	Bottle Number	Concentration
11:45	Release of gas.	1	N/A
12:00	1st Sample	2	1.82×10^{-1} sccm
12:15	2nd Sample	3	1.93×10^{-1} sccm
12:30	3rd Sample	4	1.23×10^{-1} sccm
12:45	Final Sample	5	1.4×10^{-1} sccm

Table 42 Table of first Broadmoor tracer gas experiment on July 27, 2001.

ACH based on 1st Sample and Final Sample→0.35

Experiment Two

Conditions: Same as Experiment One

Time	Operation	Bottle Number	Concentration
13:10	Release of gas.	6	N/A
13:25	1st Sample	7	1.55×10^{-1} sccm
13:40	2nd Sample	8	1.42×10^{-1} sccm
13:55	3rd Sample	9	1.62×10^{-1} sccm
14:10	Final Sample	10	1.43×10^{-1} sccm

Table 43 Table of second Broadmoor tracer gas experiment on July 27, 2001.

ACH based on 1st Sample and Final Sample→0.107

Experiment Three

Conditions: Same as previous, except staircase is up. Stack vent is (23" x 23")

Time	Operation	Bottle Number	Concentration
14:15	Release of gas.	11	N/A
14:30	1st Sample	12	1.27 x 10^{-1} sccm
14:45	2nd Sample	13	1.52 x 10^{-1} sccm
15:00	3rd Sample	14	1.53 x 10^{-1} sccm
15:15	Final Sample	15	1.48 x 10^{-1} sccm
15:15	Final Sample	17	1.20 x 10^{-1} sccm

Table 44 Table of third Broadmoor tracer gas experiment on July 27, 2001.

ACH based on 1st Sample and Final Sample→0.0756

Smoke Visualization

Time	Location	Direction/Comments
13:25	East door	In and up
13:26	Stack	Up
13:28	West door	In and up
13:29	West door	Out with wind
13:30	West windows	In
13:31	Basement	No direction
14:00	Stack	Up
14:00	West door	No flow
14:01	West window	In and steady
14:02	East door	In
14:04	West door	Out
14:05	West window	In
14:05	West door	In
14:06	West window	In
14:06	West door	In
14:09	East door	In
14:10	Stack	Up
14:11	West door	Out
14:40	East door	In
14:41	Stack	Up
14:41	West door	Out
14:42	West window	Out/In
14:50	West door	Out
14:50	Stack	Up
14:55	East door	In
15:45	East door	Out
15:50	West door	Out

Table 45 Broadmoor smoke visualization results for July 27, 2001. In/Out refers to the direction of smoke flow. In means air was flowing into the building.

Surface Temperature Readings

Time	Room	N	E	S	W	F	C	Average
11:48	Lobby	19.7	20.2	19.4	19.7	19.4	20.1	19.75
11:49	Assembly Room	19.9	19.7	20.2	20.5	20.3	20.3	20.15
11:50	Conference Room	21.4	21.8	22.7	21.9	21.2	22.3	21.88
11:50	Office	21.3	21.3	21.2	21.3	21.1	22.5	21.45
11:51	Basement	21.5	21.9	21.3	21.5	22.4	22.4	21.83
12:11	Lobby	20.2	20.1	20.3	20.6	20.4	20.8	20.40
12:12	Assembly Room	20.1	20.3	20.4	20.6	20.6	20.6	20.43
12:13	Conference Room	22.3	22.1	22.8	22	20.8	22.5	22.08
12:15	Office	21.5	21.8	22.8	21.9	21.2	22.9	22.02
12:16	Basement	21.5	21.9	21.6	21.9	21.8	21.9	21.77
12:51	Lobby	20.7	20.7	20.4	20.6	20.5	21.3	20.70
12:54	Assembly Room	20.5	20.9	20.8	20.9	20.9	20.9	20.82
12:55	Conference Room	21.7	22.3	22.8	22.3	21.6	22.9	22.27
12:56	Office	21.9	21.8	23.7	21.9	21.4	23.1	22.30
12:57	Basement	21.7	21.9	21.7	21.9	22.2	21.9	21.88
13:35	Lobby	21.2	21.2	20.9	21.3	21.2	21.7	21.25
13:36	Assembly Room	20.7	20.7	21	21.1	21	21	20.92
13:38	Conference Room	21.8	22.5	22.8	22.4	21.6	22.7	22.30
13:39	Office	22.1	22.1	23.2	22.5	21.7	23	22.43
13:40	Basement	21.3	21.9	21.7	21.8	21.5	21.8	21.67
14:21	Lobby	21.6	21.6	21.3	21.3	21.6	22.1	21.58
14:22	Assembly Room	21.2	21.2	21.3	21.3	21.3	21.3	21.27
14:23	Conference Room	22.4	22.6	22.9	22.4	22	22.9	22.53
14:24	Office	21.9	22.4	23.7	22.5	21.8	23.4	22.62
14:26	Basement	21.4	21.7	21.7	21.4	21.9	21.9	21.67
15:33	Lobby	22.1	22.2	21.9	21.9	22.1	22.8	22.17
15:34	Assembly Room	21.6	21.7	21.9	21.6	21.6	21.6	21.67
15:35	Conference Room	22.5	22.8	23	22.6	22.1	23.1	22.68
15:36	Office	22.8	23.1	23.7	22.8	22.4	23.9	23.12
15:38	Basement	21.8	21.9	21.8	21.8	22.2	22.1	21.93

Table 46 Broadmoor surface temperature readings for July 27, 2001.

Air Velocity Readings

Time	Location	1	2	3	Avg	Dir
11:57	East door middle	0.48	1.01	0.79	0.76	IN
11:59	West door	0.6	0.29	0.62	0.50	IN/OUT
12:00	West window	1.01	2.02	0.9	1.31	IN
12:18	East door middle	0.86	0.53	0.44	0.61	IN
12:20	West door	0.2	0.33	0.38	0.30	IN/OUT
12:22	West window	1.06	0.82	0.86	0.91	IN
12:27	East door middle	1.37	0.81	0.21	0.80	IN
12:29	West door	0.34	0.71	1.34	0.80	IN
12:30	West window	1.11	0.6	0.4	0.70	IN/OUT
12:31	Assembly doorway	0.13	0.13	0.04	0.10	To Stack
12:33	Stack	0.73	0.63	0.75	0.70	UP
12:58	East door middle	0.88	0.88	1.38	1.05	IN
13:00	West door	0.54	0.25	0.27	0.35	OUT
13:01	West window	1.41	1.21	0.74	1.12	IN
13:51	East door middle	0.36	0.23	0.36	0.32	IN
13:55	West door	0.4	0.26	0.24	0.30	OUT
13:58	Stack	0.88	0.89	0.93	0.90	UP
14:19	Stack (Stair up)	0.63	0.44	0.86	0.64	UP
14:20	Stack (Stair up)	0.92	0.58	0.76	0.75	UP
14:21	Stack (Stair up)	1.31	0.88	0.89	1.03	UP
14:31	East door middle	0.92	0.61	0.65	0.73	IN
14:33	West door	0.77	0.3	0.74	0.60	OUT
14:35	West window	0.25	1.1	1.02	0.79	IN
15:40	East door middle	0.4	1.35	0.45	0.73	IN
15:42	West door	0.38	0.38	0.42	0.39	OUT

Table 47 Broadmoor air velocity readings for July 27, 2001.

C.1.6 August 3, 2001

All data from loggers was downloaded. Upon inspection of weather data from the previous visit, it was found that some improbable wind values were recorded. Discussions with the weather station manufacturer pinpointed a faulty ground as the cause of incorrect readings. This was a result of the weather station being hooked up to a laptop computer that uses a power adapter with a floating ground (as opposed to a fixed ground). This caused the reference ground to fluctuate. A link isolator produced by the weather station manufacturer was subsequently installed.

Building Conditions

Window Operation: West and east louvered doors and 2 west windows open.
Stack: Staircase down.
Weather: Clear sky
Occupancy: One lobby desk worker. One full-time worker on main floor. Six camp workers in basement. Approximately 12 visitors during 3 hour monitoring period.

Air Velocity Sampling

Time	Location	1	2	3	Average	Direction
13:45	East door	0.69	1.42	0.93	1.01	OUT
13:47	West door	0.8	1.01	0.84	0.88	IN
13:48	West window	0.97	1.23	1.11	1.10	IN
13:50	Weather station	2.83			2.83	WIND
13:52	Stack	0.47	0.55	1.07	0.70	UP
13:55	East door	0.41	0.38	0.45	0.41	OUT
13:57	West door	0.47	1.07	1.09	0.88	IN
13:58	West window	1.48	1	2.2	1.56	IN
13:59	West window	1.7	1.48	1.29	1.49	IN
14:00	Stack	0.73	0.45	0.37	0.52	UP
14:23	East door	0.14	0.46	0.42	0.34	OUT
14:24	West door	1.41	1.37	0.41	1.06	IN
14:26	West window	1.18	1.14	1.7	1.34	IN
14:28	Stack	0.67	0.52	0.65	0.61	UP

Table 48 Broadmoor air velocity readings for August 3, 2001.

Surface Temperature Sampling

Lobby

Time	N	E	S	W	F	C
13:38	29.4	29.1	29.4	29.4	28.4	29.8
14:13	29.8	29.7	29.8	29.8	29.1	30.4
15:06	29.9	29.9	29.9	30.1	30.2	30.8

Assembly Room

Time	N	E	S	W	F	C
13:39	28.4	28.4	27.6	27.8	27.6	28.6
14:14	28.9	28.9	27.9	28.5	28.2	28.9
15:07	29.2	29.3	28.9	28.4	28.4	29.2

Conference Room

Time	N	E	S	W	F	C	Average
13:41	29.8	30.5	30.4	29.8	28.9	30.1	29.9
14:15	30.1	31.1	30.7	30.3	29.3	30.5	30.3
15:09	30.3	31.2	31.1	30.6	29.4	30.6	30.5

Office

Time	N	E	S	W	F	C	Average
13:42	28.4	28.8	29.2	28.9	27.8	29.9	28.8
14:17	29.4	29.6	29.3	29.6	28.3	30.2	29.4
15:10	29.6	30.1	29.8	29.9	28.7	30.4	29.8

Basement

Time	N	E	S	W	F	C	Average
13:43	24.1	24.6	24.6	24.6	23.1	24.6	24.3
14:18	24.1	24.7	24.6	24.4	23.3	24.7	24.3
15:11	24.2	24.6	24.7	24.4	23.6	25.2	24.5

Table 49 Broadmoor surface temperature readings for August 3, 2001.

C.1.7 August 16, 2001

Data from all loggers was downloaded. The weather station data appeared to be suitable.

Building Conditions

Window Operation: West and east louvered doors and 2 west windows open.
Stack: Staircase down.
Weather: Clear sky
Occupancy: One lobby desk worker. One full-time worker on main floor. Six camp workers in basement. Approximately 12 visitors during 3 hour monitoring period.

Air Velocity Sampling

Time	Location	1	2	3	Average	Direction
12:23	West door	1.31	0.71	0.83	0.95	IN
12:24	West window	0.65	2.51	1.63	1.60	IN
12:26	East door	0.69	0.75	0.58	0.67	OUT
12:27	Stack vent	0.82	0.88	0.64	0.78	UP
12:30	Basement vent	0.17	0.14	0.17	0.16	UP
12:52	East door	0.33	0.55	0.5	0.46	OUT
12:54	West door	0.42	0.42	0.89	0.58	OUT
12:55	West window	0.97	0.96	0.56	0.83	IN
12:57	Stack vent	0.3	0.66	0.27	0.41	UP
13:00	Weather station	2.86	2.08	3.4	2.78	W
13:53	East door	0.38	0	0.2	0.19	OUT
13:54	West door	0.58	0.71	0.64	0.64	IN/OUT
13:56	West window	1.13	0.48	1.13	0.91	IN
13:57	Stack vent	0.33	0.31	0.33	0.32	UP

Table 50 Broadmoor air velocity readings for August 16, 2001.

Surface Temperature Sampling

Lobby

Time	N	E	S	W	F	C	Average
12:10	23.2	23.2	23.2	23.3	22.9	23.9	23.3
12:40	23.8	23.8	23.8	24	23.6	24.6	23.9
13:35	25.2	25.1	25.1	24.9	25.1	25.7	25.2
14:27	25.5	25.5	25.6	25.6	25.3	26.2	25.6

Assembly Room

Time	N	E	S	W	F	C	Average
12:11	22.6	22.6	22.2	22.3	22.3	22.6	22.4
12:41	23.1	22.9	22.8	22.8	22.7	23.2	22.9
13:36	24.1	24.2	23.7	23.7	23.6	24.1	23.9
14:28	25.1	24.9	24.4	24.3	24.4	25.2	24.7

Conference Room

Time	N	E	S	W	F	C	Average
12:12	23.4	24.3	24.2	23.9	22.8	24.2	23.8
12:44	24.3	25.1	25.2	24.6	23.6	24.9	24.6
13:39	24.9	26.3	24.7	25.6	24.1	25.2	25.1
14:29	25.3	26.3	26.1	25.7	24.2	25.8	25.5

Office

Time	N	E	S	W	F	C	Average
12:14	23.4	23.7	24.1	23.6	23.5	24.6	23.8
12:46	23.7	24	24.2	23.8	23.1	24.8	23.9
13:40	24.8	24.8	25.2	24.8	24.2	25.8	24.9
14:30	25.2	25.6	26.1	25.9	24.6	26.1	25.6

Basement

Time	N	E	S	W	F	C	Average
12:15	22.4	22.9	22.6	22.4	22.3	22.6	22.5
12:47	22.2	22.9	22.7	22.5	22.4	22.8	22.6
13:41	23	22.9	22.7	23.3	22.9	23.3	23.0
14:32	22.5	22.9	22.8	22.6	22.3	22.9	22.7

Table 51 Broadmoor surface temperature readings for August 16, 2001.

C.1.8 August 24, 2001

All data from loggers downloaded. Sensor 2A was moved downward slightly. Sensor 2B was moved to the second attic level. The weather station's outdoor sensor was moved to the first level attic. An outdoor HOBO temperature logger was installed underneath a porch on the east.

Location	Time	N	E	S	W	F	C
Assembly Room	14:36	24.6	24.7	24.6	24.6	24.6	24.7
Assembly Room	14:46	23.6	23.4	23.4	23.3	23.6	23.6
Conference Room	14:37	25.2	25.9	25.8	25.3	24.9	25.8
Conference Room	14:48	24.3	25.1	25.1	24.6	24.1	24.9
Closed Office	14:39	25.8	25.8	26.3	25.8	25.4	26.7
Closed Office	14.49	25.2	25.5	25.8	25.6	25.0	26.3
Basement	14:41	22.9	23.2	22.9	22.6	22.6	23.3
Basement	14:51	22.8	22.9	22.9	22.6	22.6	23.1
Outside	14:43	28.8	25.8	29.8	36.7		

Table 52 Broadmoor surface temperature readings for August 24, 2001.

C.1.9 September 11, 2001

Data from loggers were downloaded.

Location	Time	N	E	S	W	F	C
Assembly Room	14:00	24.5	24.6	24.6	24.8	24.4	24.6
Basement	14:46	23.6	23.4	23.4	23.3	23.6	23.6

Table 53 Broadmoor surface temperature readings for September 11, 2001.

C.1.10 September 27, 2001

Data from loggers was downloaded. A second round of tracer gas tests was run in the Assembly Room. The loads in the assembly room consisted of one person, three fans, and one laptop computer. At 10 am, skies were clear with a westerly breeze. At 2 pm, there was 100% cloud cover. At 3:30 pm, there was 30% cloud cover. At 4:20 pm, there was 100% cloud cover.

Time	Bottle	Action	Fan	Bottle Number	Location
11:55	Room Sealed Off			2	SW
12:00	1,18,19	Release	On	3	SE
12:50	2,3,4,5	Sample	Off	4	NE
12:55	Doors Completely Open		Off	5	NW
13:19	6,7	Sample	Off	6	Center
13:50	8,9	Sample	Off	7	Center
14:10	10	Sample	Off	8	Center
14:35	11	Sample	Off	9	Center
14:55	12	Sample	Off	10	Center
15:10	13	Sample	Off	11	Center
15:30	14	Sample	Off	12	Center
15:45	15	Sample	Off	13	Center
16:00	16,17	Sample	Off	14-16	Center

Table 54 September 27, 2001 Broadmoor tracer gas bottle numbering.

Time	N	E	S	W	F	C
12:02	17.7	17.9	18.2	18.1	17.9	18
12:14	17.8	17.8	18.1	18.1	18	18
12:57	18.4	18.4	18.4	18.4	18.4	18.4
13:22	18.7	18.8	18.8	18.8	18.8	18.7
13:51	18.7	18.7	18.7	18.6	18.6	18.5
14:10	18.8	18.9	18.8	18.8	18.7	18.8
14:36	19.1	19.1	19.2	19.2	19.1	18.9
15:15	19.3	19.3	19.3	19.1	19.3	19.1
15:30	19.4	19.3	19.3	19.2	19.2	19.1
16:00	19.4	19.3	19.2	19.2	19.3	19.1
16:22	19.3	19.3	19.2	19.3	19.4	19.2

Table 55 Broadmoor surface temperature readings for September 27, 2001.

Time	East door	West door	West window	Attic
13:25	0.67 m/s	0.63	0.72	
	0.93	0.79	0.71	
13:54	0.26	0.72	1.08	0.71
	0.4	0.69	0.64	0.71
14:42	0.39	0.43	0.83	
	0.34	0.62	1.07	
15:19	1	0.64	0.84	
	0.1	0.75	1.05	
	0.55	0.54	1.06	
15:23				0.39
15:58	0.25	0.87	0.98	
	0.4	0.56	0.85	
	0.57	0.73	0.71	

Table 56 Broadmoor air velocity readings for September 27, 2001.

Time	Air Velocity (m/s)
14:05	2.62, 2.62, 2.71, 2.45, 1.82, 2.41, 2.87
14:30	2.11, 2.37, 2.7, 2.38, 2.7, 3.1

Table 57 Broadmoor weather station air velocity readings for September 27, 2001.

C.1.11 October 23, 2001

Data from loggers downloaded. Full natural ventilation through use of louvered doors ended on September 26th. On October 16th, the stack vent was shut for the season. No additional data was collected, although sensors in the attic were moved to the main floor.

C.1.12 December 18, 2001

Data from loggers downloaded. Extensive interviews with building staff were conducted. Some discussion centered around improvements that could be made to the building to enhance summertime thermal comfort. Among the suggestions was an installation of an attic fan.

C.2 CBF Summaries

C.2.1 November 23, 2000

Initial surveying of building site performed. The building was not yet open at this time. Shortly after this visit, a meeting with the SmithGroup took place.

C.2.2 March 23, 2001

HOBO Temperature Loggers installed in eight locations. Discussion of research with Roger Perry, the building manager, as well as with Chuck Foster, head of the Chesapeake Bay Foundation, took place.

Location	Time	Air velocity (m/s)
First floor window	12:42	4.8, 1.11, 0.58, 0.63, 0.81, 0.59, 1.41, 1.11, 0.79, 1.03, 0.78, 2.34, 0.22, 1.91, 2.06, 0.74, 2.61, 0.23, 1.15, 0.24, 0.83, 2.02, 0.70
First floor cubicle	12:46	0.12, 0, 0.02, 0.0, 0.0, 0.0, 0.01, 0
Second floor cubicle	12:52	0, 0.05, 0.02, 0.03, 0.16, 0.01, 0.02, 0.01, 0.08, 0.20, 0.14, 0.06, 0.03, 0.04, 0.04, 0.02, 0.06, 0.11
Second floor north window	12:57	0.64, 0.28, 0.23, 0.21, 1.24, 0.20, 0.38, 0.10, 0.42, 0.52, 0.27, 0.19, 0.36, 0.26, 0.78, 1.35, 0.23, 0.24, 0.50

Table 58 CBF air velocity data for March 23, 2001.

C.2.3 June 1, 2001

Data from loggers downloaded. Natural ventilation was not in use during this visit due to a malfunction in the system. No additional data collected.

C.2.4 July 9, 2001

Data from loggers downloaded. At 10:45 am, the building felt very cool. The fans were fairly noisy. Some loggers were moved at this time. Logger 7 was moved to the second floor fan room. Sensor 9 was moved to an upper window on the south façade. Second floor fan speeds: 2.88 m/s (center), 2.4, (right), 2.55 (bottom), 1.84 (top), 2.65 (left).

Interviews with staff members were conducted. Interviewee 1 is seated on the western portion of the second floor by a window on the north side. He only opens windows occasionally when he feels comfortable. Interviewee 2 is seated on the first floor in the eastern portion. She feels comfortable for the most part. She sometimes feels a breeze when windows are open, though she feels it is hard to make a complete assessment because windows are not used often. Interviewee 3 is seated on the second floor. She feels comfortable whenever windows are open. She noted that the previous building she worked in had bad ventilation, so she is used to high temperatures. She feels that air conditioning can be too cold. Her only quibble is that she would prefer a closed office for privacy. The open plan of the building sometimes creates too much noise to comfortably talk on the telephone or to a guest at her desk. Interviewee 4 sits on the first floor on the west side. She sees that the north windows in her section of her building are rarely opened. She never feels thermal discomfort. She points out that the building has received much publicity, including an article in the June 2001 issue of Design and Construction and the February 2001 issue of Architecture.

C.2.5 July 12, 2001

Data from loggers was downloaded. Arrived at the building at 7:20 am. The weather conditions were favorable for natural ventilation. It was sunny with a light breeze from the NW. Indoor temperature was at 23.4°C with heat pumps in operation. Outdoor temperature was at 20°C.

Window Status

Location	Time	Quantity
Second east	8:00	8 clearstory, 18 second level south facing, fan
Second west	8:00	4 clearstory, 10 second level south facing, 2 north facing
First west	8:00	10 south facing, 5 north facing
First east	8:00	18 south facing, 2 north facing, fan
First west	9:30	18 south facing, 5 north facing
All	11:45	All windows closed

Table 59 CBF window status data for July 12, 2001.

Second level natural ventilation fan (71 cm x 71 cm): centerline velocity at 7.3 m/s (8:20 am).

Air Velocity

Location	Time	South	North
First west	8:15	0.43, 0.54, 0.29	0.18, 0.38, 0.36
First west	8:20	0.77, 1.08, 1.05	0.43, 0.34, 0.37
First east	8:25	0.34, 0.24, 0.21, 1.02, 0.88	0.23, 0.26
First east	8:30	0.27, 0.70, 0.50, 0.16, 0.48	0.82, 0.35
First floor fan (150 cm x 125 cm)	NA	NA	2.07, 2.20, 2.18
First east room velocity	8:35	0.05-0.17	-
First west room velocity	8:40	0.14-0.20	-
First west	8:45	0.62, 0.23, 0.64	0.36, 0.68, 0.54
Outdoor wind speed from south deck	8:50	0.87, 1.33, 0.85, 1.06, 0.11, 0.19, 0.53, 0.50, 0.22, 0.18, 1.61, 1.63, 0.30, 1.55, 0.81 2.32, 2.63, 2.57, 2.97, 2.11, 2.22	-
Second east room velocity	9:00	0.06	-
Second west room velocity	9:00	0.05, 0.24, 0.40, 0.40, 0.27	-
Outdoor wind speed from northwest field	9:15	0.97, 1.30, 1.14, 0.20, 0.73	-
First east	10:05		0.47, 0.44, 0.53, 0.39
First west	10:05		0.46, 0.36, 0.63, 0.59, 0.37
First east	10:20	0.18, 0.16, 0.14, 0.10	
First west	10:25	0.35, 0.30, 0.23, 0.05, 0.36	
Second west	11:30		0.27, 0.25, 0.58, 0.35
First west	11:30	1.41, 0.31, 0.33, 0.61, 0.67, 1.34, 1.12	0.46, 0.63, 0.44

Table 60 CBF air velocity data for July 12, 2001.

Surface Temperatures

Location	Time	Floor	Ceiling	Furniture
Second east	9:20	25.4, 25.8, 25.2, 25.1	25.8, 26.1, 25.6	-
Second west	9:25	25, 24.4, 24.3, 24.7	24.8, 24.9, 25	-
First east	9:30	25.1, 24.2, 23.9, 24.1, 24.4	25.4, 25.6, 24.8, 25.2	-
First west	9:35	23.1, 23.6, 23.7, 23.2, 23.8	24.7, 24.2, 25.3	-
Second east	10:55	26.9, 26.3, 26.2, 26.3, 25.8, 25.9	27.3, 27.2, 26.8, 26.6	27.7, 26.6, 25.7, 26.6, 26.2, 26.8
Second west	11:00	25.5, 25.3, 25.2, 24.9, 25.1, 25.5, 25.8	26.7, 26.1, 26.2, 25.6, 25.9	25.6, 25.7, 25.2, 26.2, 25.7, 25.4
First east	11:05	26.9, 25, 24.9, 24.7	27.2, 25.8, 26.2	24.8, 26.6, 26.4, 26.8
First west	11:10	24.7, 24.8, 24.1, 24, 24.6	25.7, 24.4, 24.9, 25.2, 25.1	25.6, 25.6, 24.4, 25.8, 24.8

Table 61 CBF surface temperature data for July 12, 2001.

Person count: 1W-12, 1E-15, 2W-19, 2E-10
Outdoor temp at 10:45 am: 23 C on north, 26 C on south.

C.2.6 August 8, 2001

Data downloaded. A HOBO temperature logger was installed underneath the south deck.

C.2.7 August 10, 2001

Loggers checked. Interview with building manager indicates that clearstory windows are opening and closing erratically. The heat pumps are also running even when natural ventilation is in use. The building management system is buggy.

C.2.8 September 17, 2001

Logger data downloaded. Surveys were distributed to workers that agreed to participate beforehand. A wireless camera system was installed to monitor window operation.

C.2.9 October 11, 2001

Logger data downloaded. Conditions at 9 am: Sunny with breeze from the west. Breeze shifts to south around noon.

Window Operation

Time	1W	1E	2W	2E
10:15 am	18 south open 1 west open	18 south open Others closed	14 south open 2 north open	14 south open 1 east open
12:40pm	All windows open	18 south open	All windows open	14 south open
2:20pm				3 east windows open
7:04pm		Windows closed		

Table 62 CBF window operation data for October 11, 2001.

Atrium windows open entire visit. Upper NV fan running.

All windows closed, except atrium windows closed at 5 pm.

Surface temperature

Location	Time	N	E	S	W	C	F
Second east	11:15	24	24.6	26.8	23.7	24.7	24.1
	12:10	25	26.2	27.5	25	25.7	24.8
	13:20	24.6	25.1	26.1	24.8	25.8	24.7
	14:20	23.8	24.2	25.1	24.1	25.3	24.1
	16:11	23.3	23.1	23.3	23.2	24.3	23.3
Second west	11:18	23.8	23.2	23.4	24	25.1	22.9
	12:15	24.8	25	26.7	24.1	25.8	24.4
	13:22	25.1	24.9	26.8	25.2	25.8	24.7
	14:22	24.7	25.1	25.8	25.3	25.8	24.1
	16:14	23.9	23.9	23.9	24.8	25.1	23.2
First east	11:21	22.9	23.8	23.5	23.9	23.7	22.7
	12:19	23.7	23.6	25.4	24.4	23.7	23.1
	13:30	22.4	22.5	22.2	22.3	22.6	22.4
	14:25	22.6	23	22.1	21.8	22.8	22.4
	16:16	22.6	22.1	21.4	21.1	22.4	21.9
First west	11:25	21.1	22.4	20.9	21.4	22.1	21.1
	12:21	21.6	22.8	22.9	23.1	23.6	21.9
	13:25	22.6	23.3	22.4	22.5	23.8	22.6
	14:30	23.2	23.1	21.8	23.6	23.6	23.1
	16:11	23.1	23.1	21.2	22.7	21.4	21.2

Table 63 CBF surface temperature data for October 11, 2001.

Air Velocity

Location	Time	Air Velocity (m/s)
First east south	11:30	1.19, 2.29, 1.67, 0.34
First west south	11:34	0.97, 0.85, 0.53, 2.15
Outdoor west	11:36	0.64, 0.82, 0.92, 1.16
First east south	12:30	2.60, 2.19, 2.25, 1.77
First west south	12:33	0.26, 0.48, 0.16, 0.25
Outdoor south	12:36	1.13, 2.39, 1.89, 0.54
First east south	13:48	2.64, 2.05, 1.70, 2.13
First west south	13:50	1.28, 1.70, 0.35, 0.29
Outdoor south	13:52	1.45, 2.17, 2.68, 3.83
First east south	15:06	1.75, 2.00, 1.88, 1.78
First west south	15:09	0.17, 0.28, 0.19, 0.40
Outdoor south	15:10	0.55, 0.92, 2.37, 1.76

Table 64 CBF air velocity data for October 11, 2001.

C.2.10 October 12, 2001

Data from loggers was downloaded. At 9:30 am, it was partly sunny with a breeze from the south. All windows except those in the atrium were closed. Sensor 6 was moved outside to a stairwell off the west façade. Sensor 9 was moved to the second floor of the atrium. Additional shielding was added to the outdoor temperature sensor.

Location	Time	Window Status
First east	11:25	All north and south windows opened
Second east	11:25	All south windows opened
First east	12:45	Only 10 south windows open
Second west	13:10	All south windows opened
First east	13:45	Only 6 south windows open
All	14:30	AC turned on

Table 65 CBF window status data for October 12, 2001.

Both NV fans were running. Lower one was turned on at 11 am. The atrium windows were open the entire visit. The only unusual event was a group of approximately 15 architecture students visiting. Internal Loads: 2E-13, 2W-16, Atrium-2, 1E-20, 1W-14.

Location	Time	Air Velocity (m/s)
First east south	12:28	1.00, 1.57, 1.59, 1.54
First east north	12:30	1.14, 1.16, 1.16, 1.17
First east north	12:32	1.19, 1.13, 1.07, 1.06
Atrium	12:35	1.10, 1.27, 1.27, 0.98
Second west south	13:11	0.34, 0.41, 0.17, 0.39
First east south	13:14	1.75, 1.55, 1.53, 1.59
First east north	13:15	1.00, 0.92, 0.92, 0.93
Outside south	13:20	0.49, 0.41, 0.57, 0.77
Second west south	14:10	0.36, 0.45, 0.30, 0.50
Second west south	14:11	0.54, 0.55, 0.58, 0.41
Second east south	14:14	0.19, 0.30, 0.22, 0.20

Table 66 CBF air velocity data for October 12, 2001.

C.2.11 November 20, 2001

Interviews were conducted with survey participants. Data from all loggers was downloaded. Images from the wireless cameras were analyzed. The equipment was subsequently taken down.

C.2.12 December 31, 2001

Data from all loggers was downloaded.

C.3 Broadmoor Vent and Window Operation

Date	Open	Close	Comments
12-Jun	15:15	17:00	
13-Jun	9:00	17:00	
14-Jun	9:00	17:00	
15-Jun	8:40		
18-Jun	9:00	14:00	
19-Jun	9:00		
20-Jun	13:00	17:00	
21-Jun	9:00	17:00	
25-Jun	10:30	17:30	
26-Jun	9:00		
28-Jun	8:20		
3-Jul	12:00	13:00	
5-Jul	11:00	16:30	
6-Jul	8:50	17:00	
10-Jul	8:00	16:00	
3-Aug	9:00	15:50	Hot!
11-Aug	9:40	17:00	Almost no breeze
13-Aug	11:00	17:00	Cool-no breeze
16-Aug		15:13	Warm
21-Aug	8:45	17:00	Very humid in the morning
22-Aug	9:00	17:00	Cooler and dryer
23-Aug	9:00	17:00	Overcast
23-Aug	19:00	20:00	
24-Aug	9:00		High thin overcast
28-Aug	9:00	17:00	Sunny and muggy
29-Aug	9:00	17:00	Clear
30-Aug	9:00	17:15	Clear
31-Aug	9:00	17:00	Cloudy
5-Sep	11:20	17:00	Sunny and cool
10-Sep	9:10	17:00	Sunny and humid
13-Sep	13:30	17:05	Sunny and warm
24-Sep	13:30	17:15	Partly sunny and humid
25-Sep	10:20		Cloudy and humid
26-Sep	9:30	17:00	Clear and breezy
4-Oct	9:00	17:00	
5-Oct	9:00	17:00	Sunny

Table 67 Broadmoor east louvered door operation.

Date	Open	Close	Open %	Comments
12-Jun	9:00	17:00		
13-Jun	9:00	17:00		
14-Jun	9:00	17:00		
15-Jun	8:40	17:00		
16-Jun	9:50	17:00		
17-Jun	10:00	16:00		
19-Jun	9:20	17:00		
20-Jun	9:15	17:10		
21-Jun	9:00	17:00		
24-Jun	10:15	16:30		
25-Jun	10:30	17:00		
26-Jun	9:00	17:00		
28-Jun	8:15	10:00		
28-Jun	13:00	17:00		
1-Jul	9:45	17:00		
3-Jul	14:45	17:00		
5-Jul	9:00	16:30		
6-Jul	9:00	13:00		
7-Jul	9:45	17:00		
8-Jul	10:15	12:30		
8-Jul	13:45	16:30		
9-Jul	11:25	17:00		
10-Jul	8:00	16:00		
11-Jul	8:00	16:00		
12-Jul		16:00		
13-Jul		16:00		
14-Jul	9:45	17:00		
15-Jul	10:00	17:00		
16-Jul	10:40	17:00		
19-Jul	8:30	16:00		
20-Jul		15:30		
21-Jul	13:15	17:00		
22-Jul	9:30	17:00		
23-Jul	8:00	16:00		
24-Jul	8:10	16:00		
25-Jul	8:00			
28-Jul	9:45	17:00		
29-Jul	9:30	17:00		
3-Aug	9			
4-Aug	10	17:10	100	Not much breeze
5-Aug	9	17:00	100	No breeze
6-Aug	8:05	16:00	30	Light breeze
7-Aug	8:15	16:00	30	Light breeze
8-Aug	8:10	16:10	50	No much breeze
9-Aug	8:20	15:30	30	Light breeze
11-Aug	9:40	17:00	50	Very light to no breeze
12-Aug	9:30	16:50	100	Light breeze
13-Aug	8:30	14:45	100	Light to no breeze

14-Aug		15:30		
15-Aug	10:10	15:30	100	Light breeze to no breeze
16-Aug	8:30		100	No breeze
17-Aug	9:00	15:30	100	
18-Aug	10:15	17:00	100	Slight breeze, moderate breeze in PM
19-Aug	10:30	17:00	100	Very slight breeze all day
21-Aug	9:00	17:10	100	Very slight breeze all day
22-Aug	9:00	17:00	100	Very slight breeze all day
23-Aug	9:00	17:05	100	Very slight breeze all day
23-Aug	19:00	20:20	100	
24-Aug	9:00	17:00	100	
25-Aug	9:50	17:00	100	Little to no breeze
26-Aug	10:10	17:10	100	Light breeze
28-Aug	9:10	17:00	67	Sunny
29-Aug	9:35	17:05	67	Sunny
30-Aug	10:05		75	Sunny
31-Aug	9:10	17:10	100	Humid, light breeze, sunny to cloudy
1-Sep	10:10		100	Humid, then sunny and drier, light breeze to gusts
2-Sep	9:30	17:30	100	Nice light breeze
3-Sep	10:00	17:05	100	Sunny and cool
6-Sep	9:30		100	Cool, dry no breeze
7-Sep		17:00	100	Warm, slight breeze
8-Sep	10:10	17:00	100	Warm, good breeze
9-Sep	10:30	17:00	100	Breeze varied from none to breezy
10-Sep	9:10		50	
13-Sep	9:00		100	Warm breeze
15-Sep	12:20	14:00	50L	
16-Sep	10:00		100	Warm, slight breeze
17-Sep				Heat on to 70°F at 9:30
19-Sep		17:00		
20-Sep	10:00	17:00	50	
22-Sep	10:10	17:10	100	70s humid, slight breeze
23-Sep	9:45	17:00	100	No breeze
25-Sep				Rain!
26-Sep	9:00	12:00		Perfect day! Slight breeze
26-Sep	12:30	16:30	33	Breeze, a bit cool
29-Sep	14:00	17:00	Slight	Cool breeze
3-Oct	12:00	17:00	25	Breeze
4-Oct	9:00	17:00		Lovely breeze
7-Oct	10:00		Slight	Very cool breeze
10-Oct	12:00	14:15	Slight	Breeze, fine, then too cool
11-Oct	9:00		25	Cool breeze
13-Oct	11:15	16:00	50	No breeze, but cool
20-Oct	13:45	17:00	50L	No breeze, warm light breeze later
21-Oct	9:50	17:00	100L	Cool breeze (light)

Table 68 Broadmoor west admission area window operation. There are two windows side-by-side.

Appendix D: Thermal Comfort Surveys and Data

D.1 Broadmoor Wildlife Sanctuary

The following questions were presented to all full-time workers in October of 2001. Responses have not been edited.

1) In general, what are things about this building that work well (not solely related to ventilation)?
2) In general, what are things about this building that don't work well?
3) What is your definition of thermal comfort?
4) When you feel thermal *discomfort*, what do you do?
5) Approximate how often you feel thermal discomfort. Subjectively correlate this discomfort to factors such as air temperature, humidity, outdoor weather conditions, air velocity, number of people in the building, etc.
6) Are odors ever a problem? Where do the odors come from?
7) Is noise ever a problem? Where does the noise come from?
8) Evaluate the airflow in your work area. Is it significant enough to affect your thermal comfort?
9) What would you do to improve the building from an energy use and ventilation standpoint?
10) What do you generally wear to work during the spring, summer, fall, and winter? (Used to determine your overall insulation value)
11) What are memorable comments, both positive and negative, that you have heard the general public make on the building?
12) If possible, compare this building to other buildings you have worked in, from a ventilation and thermal comfort standpoint.
13) What do you see as the potential for natural ventilation in the United States? Would you want air-conditioning here?
14) Other comments.

Broadmoor Survey Responses

Question	Person	Response
1	EL	The lighting is excellent. Natural daylight makes work and public spaces pleasant and functional for all but the darkest days. The temperatures are generally very even-no drafts or cool spots, due to the super insulation.
2	EL	On very hot, humid, still days, the building can be too hot, but a personal fan helps make it more comfortable.
3	EL	Conditions under which I can perform in desired activities efficiently and enjoyably. If I'm writing at the computer and too cold, my fingers aren't working efficiently. If I'm running a race, I'm comfortable and writing efficiently at cooler temps.
4	EL	Add or subtract clothes; Use a fan; add heat (either personal -a heater- or heat the space in a room); Go somewhere else in or out of the building.
5	EL	Once a week in high summer. In the assembly space of the building, when there are 60+ people and the louvers are closed, it can be too hot. During a public program, there isn't the option to wear fewer clothes, or use a personal fan. As mentioned before, hot humid still conditions in an assembly or meeting are hard to counteract in the building.
6	EL	Cleaning materials can cause odors that permeate the building through the ventilation system. When the clivus multrum is heavily used, it can cause odors in the restroom.

7	EL	Sounds carry through the building via the ventilation system. Not loudly, but the ring of phones and sometimes conversations are audible.
8	EL	No-sometimes in the summer it is too small; use a personal fan.
9	EL	Try to reverse the fan from rock storage in summer to cool the building. Perhaps add photovoltaic panels on the roof.
10	EL	Spring-jeans, long-sleeved shirt, sneakers; Summer-shorts, short-sleeved shirt, sandals; Fall-similar to spring; Winter-jeans, long-sleeved shirt, sweater, sneakers.
11	EL	Regarding the toilets, "it's just like an outhouse."; "It's so comfortable in here."
12	EL	Other buildings often have stale, stagnant air or are over-air conditioned.
13	EL	Potential: great; A/C: no.
14	EL	Well, of course, I'm biased having helped plan this building, but I love it.
1	NH	Good insulation-internal temperatures are held for a long time; Excellent use of daylight.
2	NH	Difficult to cool in a hot spell-due to good insulation! Humidity is a problem for the copy machine and printer.
3	NH	Not being too hot or too cold.
4	NH	In summer, use a fan or go downstairs to cool off.
5	NH	Whenever there is a prolonged heat spell.
6	NH	Occasionally from the clivus.
7	NH	Solar fan can be noisy-as can the copier and visitors.
8	NH	With a westerly wind windows cannot be opened because papers blow. My corner can get too warm because of heat from the copier and computer and printer.
9	NH	Large floor fans in the summer.
10	NH	Layers, to put on and take off. Very light clothing in the summer, many heavy layers in the winter, and sweaters over shirts spring and fall.
11	NH	Interest in the clivus and how it works, though little boys and some adults are not happy with it.
12	NH	This has better ventilation and natural light. Summers are too hot and winters are too cold, just the opposite of buildings with central heating and A/C when the reverse is true.
13	NH	I much prefer fans and windows that open.
14	NH	None
1	CL	The heating system works very well. The sunspace and our back up stove. In the last couple of years, we have used less wood, after re-caulking of the sunspace windows.
2	CL	No answer
3	CL	No answer
4	CL	No answer
5	CL	I don't work in the nature center that often, except to clean.
6	CL	Yes, because of our increase in programs, visitors, camp all summer sometimes our toilets have odor. Also when I clean there on Sunday nights or Monday mornings. Too many people.
7	CL	Meetings, rentals, and programs, as well as summer camp.
8	CL	I do not work in the nature center that much; only to clean and do my janitorial duties.
9	CL	I don't know.
10	CL	Typically work outside.
11	CL	I have heard from not only Audubon Staff but also visitors how clean the building is kept.
12	CL	This building is one of the best.
13	CL	No A/C.
14	CL	Does not work in building much.
1	TC	Fresh air is always available in the building, although some areas get a bit stagnant. It's usually fairly comfortable, though tending to the warm side in mid-summer. Little effort is required – there's no AC thermostat to fool with. You just open doors/vents and leave them

2	TC	When it gets hot, it gets really hot. We have such a strong cultural bias to the 9-5 workday that taking a midday break and then working into the evening isn't really a viable option, but it would make sense. Since half of the office staff lives some distance from work, we're probably less inclined to work that way. My office is sort of an air trap and it is adjacent to the sunspace. It gets too warm sometimes, with little air flow.
3	TC	Being "reasonably comfortable." As a New Englander I enjoy both the heat of summer and the cold of winter. In summer I don't mind being warm, even very warm, up to a point. Outside of cities and developed areas (such as shopping centers, highways, and other places with lots of pavement and heat-absorbing surfaces) it seldom gets to the point of being uncomfortable around here. Broadmoor, being in a rural-like setting, seldom gets hot enough to be uncomfortable. If you dress for the weather and can find shade, there are very few days that feel uncomfortably hot. Comfort is relative, completely.
4	TC	The easier of either trying to change environmental factors or clothing – open or shut a window or take off or put on clothing layers. I also "think warm," or "cool," if I need to. I find that heat is much less noticeable if you stop dwelling on "what a scorcher it is." Fashion is another part of thermal discomfort, I think. Here at work we dress casually and on cloudy winter days I usually wear a fleece sweater or jacket and often wear long underwear and duck boots. I doubt that I would be thermally comfortable most days, either in summer or winter, wearing a suit and tie.
5	TC	Fairly often I feel mild thermal discomfort. Typically on Mondays/Tuesdays in summer the building is warmer than I'd think is ideal, but not so much that I'd do something about it. These would be times when the building has been closed up for the longest interval and likeliest to have gone without open windows.
6	TC	Odors from the Clivus sometimes get to the point where kids visiting say "Whew it stinks in here" when they walk into rest rooms. Odors sometimes migrate to the lobby and I've noticed visitors sort of wrinkle their noses; sometimes they'll comment or ask about the smell. A dose of peat moss down the Clivus can clear up odors very quickly – in an hour or less.
7	TC	As workspaces go, the Nature Center has a very comfortable ambient noise level. Fan noise is noticeable but not objectionable – it kind of blends in with the noise of PC cooling fans to create a white noise backdrop.
8	TC	Actually, in my workspace, airflow is insignificant enough to be a comfort factor. It can get pretty stuffy on a hot day with out a fan.
9	TC	Airflow in the building could be improved but would require a lot of duct work. Distribution of warm and cool air could be improved.
10	TC	Spring & falls from fleece sweater/vest over long-sleeved shirt, jeans or khakis, hiking boots or topsiders. Often have my sleeves rolled up. Summer: t-shirt or short-sleeved shirt, light pants or shorts, topsiders/Tevas/sneakers. Winter: same as spring/fall plus long underwear, often a heavier shirt; sometimes the down vest that I wear to work stays on for a few hours, or goes on if it gets cloudy and we don't have a fire going.
11	TC	No answer
12	TC	No answer
13	TC	No answer
14	TC	No answer
1	DF	I think the vans that blow heat from the sunspace directly into the building work well.
2	DF	Not all of the rooms are heated with solar. Due to radon remediation.
3	DF	I like to be able to wear a sweater or a vest in the cooler seasons.
4	DF	Put on or take off vest.
5	DF	In the winter I feel cold when there is a long stretch of weather where the sun doesn't shine. In the summer I feel warm if the basement doors are left open for too long. This allows in warm outside air.

6	DF	Sometimes the Clivus smells after a busy weekend or when the building had been shut-up. I'm not sure which the reason is.
7	DF	No.
8	DF	I would like to be able to have access to outside air.
9	DF	I think we need to finish the building off with some solar cells.
10	DF	Pants a sweater and vest, or shirt and vest. If it's really cold I will wear long underwear as well.
11	DF	I'm surprised when they don't know at all about the sustainable systems. They just don't notice them sometimes.
12	DF	Older buildings have no way to control heating. The only thing you can do is open up the windows and let the heat pour out. In the summer time it's just the opposite. The AC is too high and you freeze.
13	DF	In the basement it isn't a problem, but I know I would work much slower if my office were upstairs. So I think yes there is some kind of cooling system needed.
14	DF	No answer.

D.2 Chesapeake Bay Foundation Phillip Merrill Environmental Center

The following questions were presented to all thermal comfort study participants in November 2001:

1) How often do you personally open windows? Which one do you open?
2) Describe positive and negative aspects of opening windows. How would you change the natural ventilation system to work better?
3) What effect does natural ventilation have on your ability to work? Does it enhance your productivity?
4) Contrast and compare natural ventilation to air-conditioning. Which do you prefer?
5) What type of clothing do you typically wear during each of the four seasons?
6) What is your definition of thermal comfort? What is an ideal range of air temperatures in your opinion?
7) How often do you feel dissatisfied with the indoor environment? What causes this dissatisfaction? Comment on odors, noise, glare, air velocity, humidity, and air temperature.

CBF Survey Responses

Q	**P**	**Response**
1	E	Open windows once a week.
1	F	In the summer, opened two windows on the east.
1	G	Never opens or closes windows (because out of reach).
1	H	Opens windows once or twice a month on only the warmest days.
1	J	Never opens or closes windows (because out of reach).
1	K	Two times a week. Window by desk.
1	L	Open windows almost daily located directly by desk. Also open four windows on the stair atrium by mid-morning if someone else has not opened them already.
1	N	Opens window by desk once a day at least. Will open and close during day to maintain comfort level.
2	E	Loves having the option of natural ventilation. Loves having the breeze blowing in. Makes her feel healthy and awake. No negative aspects.
2	F	Likes the fresh air coming in.
2	G	Not directly impacted by windows/air flow.

2	H	System works great. Likes being able to close windows when it is too breezy or noisy outside.
2	J	Positive: fresh air, natural breezes, energy efficient. Negative: pollens, cannot reach window from desk. Must depend on compliance of those close to windows. Can get rather warm before A/C kicks back in. Everything has improved over past year though.
2	K	Fresh air, adjust local temperature are good. Negative: blowing papers when windy. Feet get cold.
2	L	NV sometimes used when it is too cold in the morning. Also humidity doesn't seem to be taken into account.
2	N	Great being able to open a window to control comfort. Fresh air makes her feel better and invigorated. Perks her up. Negative would be flying papers, but it is rare.
3	E	Enhances productivity.
3	F	It's pleasant, but does not enhance productivity.
3	G	Likes the idea of natural ventilation because reduces energy demand on heating/cooling. Feels little difference from air-conditioning, which is a benefit. Nice being able to hear sounds from outside.
3	H	Only notice naturally ventilation when too much outside noise or breeze makes papers move.
3	J	Contributes to sense of well-being. Bad for allergy sufferers.
3	K	Enhances productivity. Fresh air is refreshing.
3	L	Happy to get a breath of fresh air that enhances productivity. Warm days annoyed that windows are open which affects productivity.
3	N	Fresh air makes her more productive.
4	E	Natural ventilation far superior to A/C. Feels good knowing using less energy and the quality of air is better. A/C gives her a headache, especially going in and out of building during the day; contrast of hot/cold shocks her system.
4	F	Natural ventilation is preferred.
4	G	Air-conditioning is often too cold and impersonal.
4	H	Likes natural ventilation. A/C tends to be too cool and very dry. Fresh air is nicer than recycled air. More uniform temperature throughout the building. A/C in the building usually too cold and some areas cool differently throughout the building.
4	J	Likes the feel of natural ventilation. No re-circulated air.
4	K	Natural ventilation with A/C available for hot and humid days is preferred.
4	L	Prefer working in a building with NV. Used to office buildings where no windows open leaving you feel trapped and apart from the world. Here, you feel open and in touch with the world.
4	N	A/C can get stuffy as well as too cold. Even with the variability of NV, fresh air makes a huge positive difference. NV is preferred.
5	E	Short sleeve dresses in summer to pants and thin long-sleeve shirts in the cooler months. Building too warm for thick sweaters.
5	F	Winter: long sleeved blouses with cardigan, spring, fall, and summer: short sleeved blouses.
5	G	Overdressed during warmer months and underdressed during colder periods.
5	H	Spring and Fall: khakis and thin shirt, Summer: shorts, skirts, khakis, sandals, short sleeved shirts, Winter: khakis, jeans, long sleeved t-shirts, fleece jacket as backup
5	J	Layers even during the summer. Brings sweaters for times with A/C cools things down too much. Short sleeve shirts during winter when morning sun is strong.
5	K	Slacks and short-sleeved shirts during summer. Slacks and long sleeved shirts for the fall and spring.
5	L	Spring: lightweight suits and dresses, Summer: shorts and t-shirts, Fall: slightly heavier suits and some sweaters, Winter: heavier business suits or sweaters.
5	N	Always layered during the seasons. Wear cotton blouses and turtlenecks with sweater or light jacket.
6	E	Like things cooler than most people during winter. Happy at 65 degrees.
6	F	Doesn't know.

6	G	Preferred temps in the mid 60s.
6	H	Thermal comfort means temperature is not noticeable. 68-72°F is good range.
6	J	65-75 degrees. Likes things on cooler side.
6	K	68-72°F. Thermal comfort is neutral to very slightly cool or very slightly warm sensation.
6	L	Thermal comfort means not sweating and not being at all cold. Ideal temp between 67-70°F.
6	N	Thermal comfort is being able to work, meet, and eat when the temperature does not affect thinking. Winter: 68-72°F. Summer: 74-76°F.
7	E	Solar gain intense on some days. Noise from co-workers occasionally a problem. Humidity problem in the summer, but not during fall.
7	F	Air velocity can be annoying.
7	G	Not dissatisfied often. Glare a problem during the winter. White noise is sometimes pretty noisy. Rarely too cold, sometimes too warm.
7	H	Difficult to concentrate with construction noise sometimes. Got humid two or three times over the summer, but building manager very responsive.
7	J	Glare was original problem. Hardly any odors compared to other buildings. Temperature and air velocity good. Likes feeling of light draft.
7	K	Rarely dissatisfied. Temperature is main complaint.
7	L	Dissatisfied with indoor environment once a week. Can take 30 minutes to adjust to building in the morning.
7	N	Only time dissatisfied is in conference facility where windows are not operable. Notice odors of food, which is a good thing. When there is a problem, the building manager is notified and makes adjustments.

D.2.1 CBF Thermal Sensation Data

TS Morning	2E	2E	1E	2W	1W	1E	2W	1E	2W	2E	1W	2W	A	2W	Average
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	
17-Sep			1		2			0		0		1		0	0.7
18-Sep		1	0		0			0	0			1	-1	0	0.1
19-Sep		0	1	1	0		1	-1	0	1		0	0	0	0.3
20-Sep	2	0	1	0	0			1				2	1	0	0.8
21-Sep	2	1	0	1	0		0	1				1	1	-1	0.6
24-Sep	-1	2	-2		-2		1	-1				0		-2	-0.6
25-Sep			0	2	0		1	0				0			0.5
26-Sep	-1	0	0	1	-2			-1				0	0	0	-0.3
27-Sep	0		0		0			-1				0	-2	0	-0.4
28-Sep	0		0					0				0	0		0.0
1-Oct			-1		0		0	0	0						-0.2
2-Oct	0		0	1	0	2		0							0.5
3-Oct	-2	0	0	0	0		1	0							-0.1
4-Oct		1	1	1				0					1		0.8
5-Oct		0	0	2			0	0		0			0	1	0.4
8-Oct		1	0					0		1		0	0	-1	0.1
9-Oct	0	0	-1				0	0		-1	0	0	0		-0.2
10-Oct			out	1	0	2	1	0		1	0	0	-1	0	0.4
11-Oct						2		0		1	0	0	0	0	0.4
Average	0	0.5	0	1	-0.2	2	0.6	-0	0	0.4	0	0.4	-0	-0.3	**0.2**

Table 69 CBF morning thermal sensation data for September 17 through October 11, 2001.

TS Afternoon	2E	2E	1E	2W	1W	1E	2W	1E	2W	2E	1W	2W	A	2W	Average
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	
17-Sep	2	0	1	-1	0	0		0	-3	1			0		0.0
18-Sep		0	1		0			-1	2	0		2		0	0.5
19-Sep			0	1	0		0	0	1			1	1	0	0.4
20-Sep	0		0	0	1			1	-1			1	-1	0	0.1
21-Sep	0		-1	0	-1	1	0	-1				0	0	0	-0.2
24-Sep	0		-1				1	0				1	-3	-2	-0.6
25-Sep	0	1	0	1	0			0		-1		0			0.1
26-Sep			0					-1				0	-1	0	-0.4
27-Sep		-2	0	2	0	3		-1				0	0		0.3
28-Sep			0			3		0				0	2		1.0
1-Oct			0		0		1	0	-2						-0.2
2-Oct	0		0	1	0	3		0							0.7
3-Oct	-3	0	-1	1	0			0							-0.5
4-Oct			0					0				2			0.7
5-Oct		1	0		0		1	1		-1			0	-2	0.0
8-Oct	2		0					0		1		0	0	-2	0.1
9-Oct	-2	1			0		1				0	0	0		0.0
10-Oct						-3	0	0		-1	0	0	0	0	-0.5
11-Oct											0		-1		-0.5
Average	-.11	.14	-.06	.63	0	1.2	0.57	-.12	-0.6	-.17	0	0.54	-.23	-.67	**0.1**

Table 70 CBF afternoon thermal sensation data for September 17 through October 11, 2001.

TS Morning	2E	2E	1E	2W	1W	1E	2W	1E	2W	2E	1W	2W	A	2W	1W	
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**Avg.**
15-Oct	0		0		1		0		1		-1		0			0.14
16-Oct	0		0		0				-3		-2		0		-2	-1.00
17-Oct			0		0		0				0	-1	0	-2		-0.43
18-Oct		0	0				0				-1	0	0	-1		-0.29
19-Oct			0				0	-1			0	0	-1	0		-0.29
22-Oct	0	0	1				0	0		2	0	-1	1	1	0	0.36
23-Oct	0		1		0		0	0		2	0	1	0		-1	0.30
24-Oct	1	0	0		0			0	0		1	0	0			0.22
25-Oct	2	1	1		1			1	0		1	0	1	1	1	0.91
26-Oct		-2	0		-1	0	0	-1	0	-1		0	0	-2		-0.64
29-Oct	2	0	0				0	1		0		0	0			0.38
30-Oct		1	0		0	-2	-1	-1	0	2	0		0	-2		-0.27
31-Oct					1			-1		2	0	0	0	0		0.29
1-Nov							0	0	0	1	0		0	0		0.14
2-Nov	0							0	2	1	1		0	-1		0.43
5-Nov	2	0					-1	1	-1	0	0	0	0	0	0	0.09
6-Nov		1			0			0				1	0	0		0.33
7-Nov					1		0	0	-1	2	-1	2	0	0	0	0.30
8-Nov					0	-3				2		1	0	0	-2	-0.29
9-Nov								0		2		0	0	0		0.40
12-Nov	2				0		0	0		1		2	0	0		0.63
13-Nov							1	0		2		1	0	0		0.67
14-Nov	0						0	-1		1		1	0	0		0.14
15-Nov		-1			0			0	0	0		1	0	0		0.00
16-Nov		1			0			0					0	0		0.20
19-Nov					-1		0	0					1	0		0.00
20-Nov		0									0		0	-2		-0.50
Total	.82	0.08	0.25		.13	-1.7	-.06	-.10		1.2	-.13	.42	.07	-.36	-.57	0.08

Table 71 CBF morning thermal sensation data for October 15 through November 20, 2001.

TS Aft.	2E	2E	1E	2W	1W	1E	2W	1E	2W	2E	1W	2W	A	2W	1W	
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	Average
15-Oct			0		0		1		1		0		-2			0.00
16-Oct			-1		0				-3		0	0	0			-0.67
17-Oct			0		0		1				0	0	0	-1		0.00
18-Oct		3					1		3		1	0	0	-1		1.00
19-Oct			0				0	0	2		-1	0	-1	0		0.00
22-Oct	0	1					1	0		-1	0	1	1	2	1	0.60
23-Oct	0		0		1		0	-1		-1	1	0	0			0.00
24-Oct	0		0		0			0	0		0	0	1			0.13
25-Oct		0	1					0		0	-1	0	0			0.00
26-Oct		0	0		0	0	0	0		-1		0	-1			-0.22
29-Oct	2		-2				0	-1		3		1	0			0.43
30-Oct		0	0		0	-2		-1	1	0	0	0	0	-1		-0.27
31-Oct					1			-1		0	1	0	0	0		0.14
1-Nov	3							0	0	-1	0		-1	0		0.14
2-Nov	1							-1		-2	0		0	0		-0.33
5-Nov	0	0					-1	-2	-3	-1	1	0	0	-2	-2	-0.91
6-Nov		2			0			0		-1	0	0	0			0.14
7-Nov	3				0		0	0	1	0		1	0	-2		0.33
8-Nov					1	-3		-1		0		1	0	-2		-0.57
9-Nov								-1	3	2		0				1.00
12-Nov	3				0		1	0		0			0	0		0.57
13-Nov								1		3		2	0	-1		1.00
14-Nov	3						1	0	0	0		1	0			0.71
15-Nov		1			0			0	0			1	0	0		0.29
16-Nov					0			0					0			0.00
19-Nov					0		1	-1					0	1		0.20
20-Nov																
Total	1.5	.88	-.20		.20	-1.7	.46	-.41	.42	0.0	.13	.40	-.12	-.47	-.50	0.14

Table 72 CBF afternoon thermal sensation data for October 15 through November 20, 2001

D.2.2 CBF Air Velocity Sensation

Date	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Average
	2E	**2E**	**1E**	**2W**	**1W**	**1E**	**2W**	**1E**	**2W**	**2E**	**1W**	**2W**	**A**	**2W**	
17-Sep				1					2			1	1	1	1.20
18-Sep			3			1		1	1	2		1	1	1	1.38
19-Sep			2		3	2		5	1	3		2	1	1	2.22
20-Sep			3		1			1	2			1	1	1	1.43
21-Sep			3		1		2	1				2		2	1.83
24-Sep	0		4				1	1					1	2	1.50
25-Sep	0		2					1		2					1.25
26-Sep			2					1						2	1.67
27-Sep	0		2					1						1	1.00
28-Sep			3					1							2.00
1-Oct			3				1	1							1.67
2-Oct	0		3					1							1.33
3-Oct	0							1							0.50
4-Oct								1							1.00
5-Oct			4					1						2	2.33
8-Oct			3					1		3		1		3	2.20
9-Oct								1		1	2	1			1.25
10-Oct								1			2	1		1	1.25
11-Oct								1		2	1	1			1.25
Average	0		3	1	2	2	1	1	2	2	2	1	1	1.545	**1.49**

Table 73 CBF air velocity sensation for September 17 to October 11, 2001. (0 = no air movement, 5 = flying papers).

Appendix E: Building Data

E.1 Broadmoor Wildlife Sanctuary Nature Center

Location	Dimension	Quantity
North assembly room windows (single-glazed, summer; triple, winter)	31 x 27" upper portion	3
	31 x 27" lower portion	3
	18 x 26"	1
North bathroom windows (double-glazed)	28 x 20"	4
West entrance doors (single-glazed)	36 x 27"	2
West windows (admissions area, double-glazed)	23 x 27" upper portion	2
	23 x 27" lower portion	2
South windows (admissions area, double-glazed)	23 x 27" upper portion	2
	23 x 27" lower portion	2
South windows (adjacent to sunspace and trombe wall, triple-glazed)	23 x 27" upper portion	3
	23 x 27" lower portion	3
South doors (conference room, double-glazed)	65 x 26"	2
South glazing (adjacent to sunspace, double-glazed)	73.5 x 46"	2
South light shield window (admissions area, double-glazed)	26 x 68"	1
South light shield window (conference room, double-glazed)	26 x 68"	1
Total north fenestration	4.987 m^2	
Total west fenestration	2.85 m^2	
Total south fenestration	6.06 m^2	
Total east fenestration	0	

Table 74 Broadmoor fenestration locations and areas.

E.2 Phillip Merrill Environmental Center

CBF Window Schedule

	Quantity								
1st Floor	**North**	**East**	**South**	**West**	**Area per unit**	**N area**	**E area**	**S area**	**W area**
Type-1	13	4	0	4	1.82	23.66	7.28	0.00	7.28
Type-10	0	0	20	0	8.01	0.00	0.00	160.28	0.00
Type-11	0	1	2	1	6.38	0.00	6.38	12.76	6.38
Total for floor						23.66	13.66	173.04	13.66
2nd Floor									
Type-2	14	4	0	4	1.44	20.16	5.76	0.00	5.76
Type-3	17.5	0	0	0	1.97	34.44	0.00	0.00	0.00
Type-5	4	0	0	0	8.18	32.72	0.00	0.00	0.00
Type-7	2	0	0	0	5.12	10.25	0.00	0.00	0.00
Type-12	0	0	18	0	9.04	0.00	0.00	162.79	0.00
Type-13	0	1	4	1	5.40	0.00	5.40	21.62	5.40
Type-14	0	0	22	0	7.14	0.00	0.00	157.10	0.00
Total for floor						97.57	11.16	341.51	11.16
Total for Side						**121.23**	**24.83**	**514.55**	**24.83**

Wall Area (m^2)

	North	East	South	West
1st Floor	275.92	50.80	275.92	50.80
2nd Floor	235.90	43.43	235.90	43.43
Clerestory	0.00	30.10	245.26	30.10
Total	511.82	124.32	757.09	124.32
Floor Area	1300.00			
Net Wall Area	390.60	99.49	242.53	99.49

Volume (m^3)

Clerestory	2017
2nd Floor	2910
1st Floor	3404
Total	8331

Table 75 CBF window schedule as given by SmithGroup architectural plans.

Appendix F: Other Naturally Ventilated Buildings

Special thanks to Ove Arup's San Francisco office for providing some of this information.

Montana State University EPICenter, Bozeman, MT **Sponsor:** National Institute of Standards and Technology	Current 2000	Passive ventilation, passive heating and cooling, daylighting, fuel cells, photovoltaic panels, sustainable materials, goal of LEED platinum
Davis L. Lawrence Convention Center, Pittsburgh, PA **Architect:** Burt Hill Kosar Rittelmann Assoc.	Current 2000	Natural ventilation, low temperature air delivery, displacement ventilation, raised floor air supply plenum in meeting rooms, daylighting, geothermal cooling
Seattle Opera House Mercer Center Complex, Seattle, Washington **Client:** Seattle Center **Architect:** Loschky Marquardt Nesholm	Current 2000	Scheme design for the renovation of a 1960s Opera House, central plant and arena. The Opera House is being renovated to maximize natural ventilation
Lucasfilm Digital Center at the Presidio Letterman Complex, San Francisco, California **Client:** The Presidio Trust and Lucasfilm **Architect:** Gensler Associates	Current 2000	Mechanical, electrical and plumbing engineering and sustainable design for the winning competition scheme for the 100,000 m² Letterman Complex development at the Presidio. The complex will be silver LEED rated with daylighting, natural ventilation and other energy efficient features throughout. The site will include a "great lawn' for public access and a museum developed by Lucasfilm that will focus on the history of the Presidio. Also planned are a café, educational facilities and underground parking
Science Building, Colorado College, Colorado **Client:** Colorado College **Architect:** Moore Ruble Yudell	Current 2000	Mechanical, electrical and plumbing engineering design for 140,000 ft² laboratory and research facility using natural ventilation, daylighting and other sustainable design features.
San Jose Fire Station No. 1, California **Client:** City of San Jose **Architect:** RMW Architecture & Design	Current 2000	Mechanical, electrical and plumbing engineering for the natural ventilation, daylighting and sustainable design of a new fire station
School of Nursing and Biomedical Sciences, University of Texas, Houston, Texas **Client:** University of Texas **Architect:** Patkau Architects	Current 2000	Structural, mechanical, electrical and plumbing engineering systems assessment and design for a new 25,000 m² school of nursing. This will be the first sustainable building on the University of Texas campus and includes daylighting, natural ventilation, photovoltaic panels, and rainwater collection system among other low energy design features

275 Sacramento Street, San Francisco, California **Client:** Patson Development **Architect:** Heller Manus Architects	Current 2000	Structural, mechanical, electrical and plumbing engineering for a new 8-story, 7,800 m² speculative office building in downtown San Francisco. The facility includes offices and ground floor retail spaces and features several energy efficient design features such as natural ventilation and daylighting
Interdisciplinary Sciences Laboratory University of California at Santa Cruz, California **Client:** University of California **Architect:** Moore Ruble Yudell	Current 2000	Mechanical, electrical and plumbing engineering design for a new 8,000 m² interdisciplinary sciences building designed with natural ventilation and perimeter heating in the offices and mechanical ventilation in the classroom space, natural ventilation and daylighting
Lamont-Doherty Earth Observatory, The Palisades, New Jersey **Client:** Columbia University **Architect:** Rafael Vinoly Architects	Current 2000	Structural, mechanical, electrical and plumbing engineering for a 2700 m² office and conference rooms for scientists overlooking the Hudson River. Included in the design are mid-season natural ventilation and a VAV system
Seattle Opera House Mercer Center Complex, Washington. **Client:** Seattle Center **Architect:** Loschky Marquardt Nesholm	Current 2000	Scheme design advice and sustainable consultancy for the renovation of a 1960s opera house, central plant and arena to maximize natural ventilation
Shaklee Corporate Headquarters, Pleasanton, California **Client:** Shaklee Corporation **Architect:** Gensler Associates	Completed 1999	Mechanical, electrical and plumbing engineering design for a new 26,500 m² corporate office complex. Phase 1 included facilities for offices, conference center and cafeteria. Design is for maximum energy efficiency, utilizing natural ventilation, raised floors, daylighting and recycled materials
California College of Arts and Crafts - Beta Building, San Francisco, California **Client & Architect:** Tanner Leddy Maytum Stacy	Completed 1999	Structural, mechanical, electrical and plumbing engineering design for the transformation of an existing Greyhound bus maintenance building into a fine arts educational facility. Low energy systems used to meet state and city requirements were roof mounted solar panels and radiant floor slab heating
Public Safety Building, Berkeley, California **Client:** City of Berkeley **Architect:** Holt Hinshaw/Ekona	Completed 1998	Mechanical engineering consultancy for a natural ventilation scheme for a new public safety building
Douglas Hall Library, Menlo School, Atherton, California **Client:** Menlo School **Architect:** David Bartlett Associates	Completed 1998	Mechanical, electrical and plumbing engineering design for conversion of a landmarked residence to a naturally ventilated library, office, and classroom space with a 2,000 m² addition

Gap Inc. 901 Cherry Office Building, San Bruno, California **Client:** The Gap/William Wilson & Associates **Architect:** William McDonough Architects/Gensler & Associates	Completed 1998	Structural, mechanical, electrical and plumbing engineering and telecommunications consultancy for a 34,000 m^2 phased office complex. Phase 1 of the facility, 19,500 m^2, is highly energy efficient and can operate as a naturally ventilated or air-conditioned building via a floor air supply system. The building uses thermal mass for precooling and a sod roof to provide insulation and reduce rainwater run off. The design features an exposed eccentrically-braced frame, a cost-effective solution for its location in seismic zone 4, extensive use of daylighting and re-use of recycled material wherever possible
McConnell Foundation Headquarters, Redding, California **Client:** McConnell Foundation **Architect:** The NBBJ Group	Completed 1998	Structural, mechanical, electrical and plumbing engineering for a 3,000 m^2 office complex with library and meeting roofs with video teleconferencing capabilities. The building can operate as a naturally ventilated or air-conditioned building. Low energy design included use of daylighting and recycled materials for timber structure and the use of an adjacent lake to provide for heat sink for the air conditioning system
Phoenix Federal Courthouse Studies, Phoenix, Arizona **Client:** General Services Administration **Architect:** Richard Meier & Partners/Langdon Wilson Architects	Study Completed 1997	Environmental studies to provide natural ventilation in a 5,800 m^2 glass atrium that is glazed on two sides and flanked by mechanically air-conditioned offices and courtrooms on the other sides. Computer modeling of the atrium space studied the full range of environmental conditions anticipated over a typical year using a variety of passive environmental control systems including evaporative cooling systems, solar heating of the space, natural ventilating effects, use of conditioned air from adjacent balconies, shading elements and glazing treatments
Carmel Mountain Ranch Public Library, San Diego, California **Client:** San Diego Public Library/ Carmel Mountain Ranch Public Library **Architect:** MW Steele Group	Completed 1997	Structural, mechanical, electrical and plumbing engineering for a 1,300 m^2 new single story library featuring natural ventilation and shading devices incorporated to moderate climatic effect. There is double-height central space with a turret for air venting. A back-up "peak-trimming" ventilation system is used only on the hottest days of the year
San Francisco Ballet Pavilion, California **Client:** San Francisco Ballet **Architect:** Simon Martin-Vegue Winkelstein Moris	Completed 1996	Structural, mechanical, electrical and plumbing engineering for the design of a 2,300 seat, naturally ventilated temporary performance space for the San Francisco Ballet

UCSD Engineering Unit II, San Deigo, California **Client:** University of California San Diego **Architect:** Zimmer Gunsul Frasca	Completed 1994	Structural, mechanical, electrical and plumbing engineering, acoustic/vibration and communications consulting and input to DPP and design for 13,000 m^2 research and teaching facility for the departments of Engineering and Computer Science. The building consists of two separate lab and office structures. Both structures are concrete shear walls, utilized for the vibration damping characteristics of concrete. The naturally ventilated office building is five stories, and incorporates operable sash windows and external shading. The structure is a concrete beam and slab solution to keep floor-to-floor heights to a minimum. The structure of the laboratory building is fully integrated with its servicing requirements, and provides for future flexibility and adaptability

Appendix G: Wind Pressure Coefficients

Wind direction	Cpl	Cp2
270° (W)	0.4	-0.3
292.5	0.3	-0.4
315	0.2	-0.5
337.5	-0.2	-0.55
0 (N)	-0.6	-0.6
22.5	-0.55	-0.2
45	-0.5	0.2
67.5	-0.4	0.3
90 (E)	-0.3	0.4
112.5	0.25	-0.22
135	-0.5	0.2
157.5	-0.55	-0.2
180 (S)	-0.6	-0.6
202.5	-0.2	-0.55
225	0.2	-0.5
247.5	0.3	-0.4

Table 76 Broadmoor wind pressure coefficients [Santamouris & Asimakopoulous, 1996]. The values selected assume that only inlets and outlets on the west and east side of the building will be open. The values are taken for a 2:1 length-to-width ratio, low-rise building, with partially shielded conditions.

Wind direction	Cpl	Cp2
0 to 11.25° (N)	0.5	-0.7
11.25 to 33.75	0.375	-0.75
33.75 to 56.25	0.25	-0.8
56.25 to 7.75	-0.125	-0.65
78.75 to 101.25 (E)	-0.5	-0.5
101.25 to 123.75	-.125	-0.65
123.75 to 146.25	0.25	-0.8
146.25 to 168.75	0.35	-0.75
168.75 to 191.25 (S)	0.5	-0.7
191.25 to 213.75	0.275	-0.75
213.75 to 236.25	0.2	-0.8
236.25 to 258.75	-0.15	-0.65
258.75 to 281.25 (W)	-0.5	-0.5
281.25 to 303.75	-0.125	-0.65
303.75 to 326.25	0.25	-0.8
326.25 to 348.75	0.35	-0.65
348.75 to 360 (N)	0.5	-0.7

Table 77 Chesapeake Bay Foundation wind pressure coefficients [Santamouris & Asimakopoulous, 1996]. The values selected assume that optimal combinations of windows will be open. The values are taken for a 2:1 length-to-width ratio, low-rise building, with unshielded conditions.

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