Natural Ventilation Possibilities for Buildings in the United States

by

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the Requirements for the Degree of

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ABSTRACT

In the United States, many of the commercial buildings built in the last few decades are completely mechanically air conditioned, without the capability to use natural ventilation. This habit has occurred in building designs since the designers do not have the tools to understand the impact of using natural ventilation as an option in conditioning a building.

Research has been conducted to create a better understanding of how natural ventilation can be used successfully in building designs. First, understanding the buildings that currently use natural ventilation and secondly by analyzing how buildings can operate in different climates. It is important in the building design industry to know the feasibility of designs, and is therefore important to see buildings that have used natural ventilation techniques. It is also important in the building design industry to know if the natural ventilation techniques that have been used, can be used in the climate that a building needs to be designed for.

It was determined that increased airflow through natural means can significantly enhance the functionality of buildings in the United States. Throughout the United States there are numerous hours when outdoor conditions suggest using natural ventilation for a primary cooling system. Natural ventilation can help a building maintain comfort for the occupants, reduce energy usage, reduce cooling equipment size and increase indoor air quality. With the use of a natural ventilation design tool, designers can understand the impact that each of the buildings major features has on the overall comfort or energy required to make it comfortable.

Thesis Supervisor: Leon R. Glicksman
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Many Thanks,
Brian N. Dean
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Chapter 1 Introduction

Natural ventilation is a form of air movement through a space without the means of mechanical support. The use of natural ventilation can lower the energy needed to condition an occupied space.

The cooling energy needed to condition a building is determined by how the heat is removed from the conditioned spaces. The air can be cooled by an air conditioner or the air can be exchanged with outside air naturally or mechanically. The floor plan design is important to determining how the air flows through the space, to move the energy loads out naturally.

The cooling energy is also determined by how much energy enters or is created in the conditioned space. The load will be minimized by properly designing solar protection to block solar energy loads from entering the space. The equipment and lighting design is also important in minimizing the energy created in the space. The floor plan design is important in locating high energy loads, including people, computers and lighting near operable openings to move high energy loads out of the space naturally.

In the United States, residential buildings are typically built with the capability of using natural ventilation, but often the other buildings built do not have this capability. There is a challenge to get the buildings that are currently being built to have the capability to use natural ventilation. Following that there is also a challenge to get the users or controls of the buildings that do have the capability to use natural ventilation to use natural ventilation properly. This research shows examples of buildings that successfully use natural ventilation to minimize their cooling energy use. This research also creates a tool to help designers understand when natural ventilation can be used for energy savings over the life of the building.

The public knowledge of natural ventilation: Articles and readings of what the industry knows and how natural ventilation is integrated into building design.

Many discussions have occurred throughout the world regarding the benefits to designing buildings with natural ventilation, and yet many of the newest buildings are not capable of utilizing natural ventilation. At Healthy Buildings 2000 a workshop was held concerning ventilation standards, with discussions to better understand the research needs and natural ventilation. Much of the discussion seemed to explain how natural ventilation could possibly fit into already established mechanical ventilation standards. This shows that there is concern in the industry as to how reliable natural ventilation can be.

The benefits of natural ventilation have been documented in many cases, and Dr. Donald Aitken of the Renewable Energy Policy Project talks in his report on “Whole Buildings and Whole Buildings Policies” about how increased productivity of the occupants is reason enough to consider better building technologies such as natural ventilation.
ventilation. "Even a 1% improvement in employee productivity or reduction in absenteeism provides benefits equal to saving 70–100% of the cost of energy." In addition the report asserts that the personal improvements include lower "employee absenteeism, increase retail sales, and performance of students in schools, and that these improvements tend to be more on the order of 5–15% rather than just 1%."<1> Natural ventilation can be a very economically viable technology when considering these personal benefits.

In an article from Architectural Record, in May 2000, Nadav Malin writes for architects about the advantages of natural ventilation with regard to energy savings and personal control. In particular, it is stated that natural ventilation will have energy savings "in the range of 10 to 25 percent compared to similar buildings without natural ventilation." It is interesting from this architectural magazine that the blame for not using natural ventilation is stated that "most engineers prefer not to deal with the variable of occupants undermining the mechanical system by opening windows when the equipment is operating." <23>

* Natural Ventilation Discussion and Research: This section will look at the understanding of natural ventilation prior to creating the NV design advisor.

Santa Monica, California is a good example to look at for understanding what policy and design considerations have been made with regards to energy efficient building in general. In 1994, Santa Monica created the Sustainable City Program, to move away from "conventional design and construction methods that produce buildings that can negatively impact the environment as well as occupant health and productivity." As part of the Green Building Design and Construction Guidelines that were developed for this program, computer energy simulations are encouraged "throughout the design process." In addition the guidelines suggest a combination of design strategies, which include natural cooling and ventilation. In addition, the guidelines note that an effective design will account for the climate-specific conditions at the building site. <30>

Florida Power and Light uses their "Home Energy Solutions" portion of their website to give advice concerning how to save energy in homes, primarily targeted toward housing in Florida. In this information they explain how to create both cross building ventilation and buoyancy driven air movement, as natural ventilation to "reduce or even eliminate air conditioning costs."<15>

In Utah, the Utah Card website also offers information to promote the use of natural ventilation. They note that natural cooling can occur with the use of "high ceilings, indoor and outdoor shutters, and floor to ceiling windows," in building designs. Also they suggest opening windows at night, close shutters when the sun hits the building, and use the stack effect with a low window on the cool side and a high window on the hot side of the building. <35>

At the Norwegian Building Research Institute, there has been research regarding natural ventilation in office buildings, which "indicates a need for assisting fans" with
office buildings in Europe. This report, focused on how to use heat recovery concepts with natural ventilation, also says that the most effective use of advanced natural ventilation systems is in the "cold climate countries." It is also stated that in the moderate climate countries, standard natural ventilation systems are "common practice, using wind and thermal buoyancy as the driving forces." <27>

Researchers at MIT and Harvard, in Cambridge, Massachusetts have also been working on Healthy Building issues. In a paper by Spengler and Chen, they note that "compared to mechanical ventilation systems, natural ventilation systems consume little energy, require little maintenance, have low first costs, and are environmentally friendly. In terms of indoor air quality (IAQ), they state that the placement of the inlets for the natural ventilation should be "where the outdoor air quality is better than the indoor air quality." It is also suggested that cities such as Hartford, Connecticut; Madison, Wisconsin; Ely, Nevada; Medford, Oregon; and Fresno, California have the potential to use natural ventilation as the only cooling system when properly designed. Additionally they suggest that a series of other cities, including Miami, Florida and Los Angeles, California would benefit from the use of natural ventilation in the Spring and Fall. In addition this paper asserts that "mechanical ventilation is inevitable"<31> due to the lack of control and consistency with natural ventilation.

This thesis leads through a series of studies looking at existing buildings, buildings in their design phase, and features that could be designed to use natural ventilation in buildings. Chapter 2 is organized as a study of existing buildings and building designs that use natural ventilation. Chapter 3 is organized as series of reports that lead toward the development of a simple natural ventilation design tool. Chapter 4 discusses the creation of the natural ventilation design tool, including the methodologies and simplifications that were used to create a useful tool. Chapter 5 is used to summarize the possibilities for natural ventilation in the United States. In the Appendices there is useful information to help the reader both understand this document and be able to gather additional information on buildings that use natural ventilation.
Chapter 2 Natural Ventilation Studies
Section A: Natural Ventilation Concepts

Natural ventilation is a form of air movement through a space without the means of mechanical support. The natural means of support that make natural ventilation work include wind and change in air density based on temperature difference. Natural wind driven ventilation can be used on any building design with large or multiple windows to allow the air to move through the space. Natural buoyancy driven ventilation can be used in any weather condition with proper building design that promotes hot air to rise through the space.

Natural Wind Driven Ventilation
To have wind create air movement through a space in the building, the major factor is the positioning of the windows. First, the window positioning should be designed to place the largest window or building surface area facing the prevailing cooling season wind direction, or the most common wind direction for the site during the cooling season. Second, the window size, shape and position on the wall should allow for wind to be caught from its flow path to move into the building. Third, the positioning of a second window should allow for the air to move through and out of the space, with little resistance from objects like walls or furniture.

Natural Buoyancy Driven Ventilation
To have buoyancy create air movement through the building, both temperature and height difference between the inlet and the outlet are important. The first case to create air movement though buoyancy is to have two window openings separated by height, which allows cool air to move through the lower window and warm air to move through the higher window. The second case is to have a chimney or stack to create a larger height difference, with the warm air exiting through the top of the stack. And the third case is to have openings at the top of an atrium, such that cool air can move from the outside wall through the space and the warm air can move out through the opening in the roof.

Figure 1. Natural Wind Driven Ventilation – Cross Building Ventilation
In addition to these typical natural airflow patterns, there are also combination airflows that have different airflow rate and direction depending on indoor and outdoor conditions, rather than the design of the building. Considering these airflow possibilities will allow the designer to understand that the building may need multiple
design strategies to achieve maximum possible airflow. Often the better designs will have an airflow strategy for high wind speed and a separate strategy for no wind.

At the University of Hong Kong, China, the school of architecture has teachings of how to design buildings capable of using natural ventilation. An important concept that shows the usefulness of natural ventilation is that “energy free ventilation is always desirable” when the outdoor conditions allow for comfortable indoor conditions. Although it is noted that in hot and humid climates there is more chance for designing natural ventilation in “residential and institutional buildings than commercial buildings,” because of the consistent daytime occupancy and high building heat loads. This shows that there is still challenge and lack of confidence in the ability to use natural ventilation beyond residential buildings, due to the higher energy loads and lack of user ownership for controlling ventilation openings.

The following is a list of characteristics that are important when designing a naturally ventilated building:

1. **Inlet and Outlet Position:** Design the air outlet at the highest point and air inlet at the lowest point possible in the building, to allow the cool air to come in and the hot and humid air to move up and out through the highest point.
2. **Building Depth:** Design a narrow building to allow air to move with less resistance across the building. “The maximum width that you could expect to ventilate naturally is estimated at 45 ft.”
3. **Interior Layout:** Position vertical barriers parallel to the natural airflow: this will minimize air resistance and will allow the air to flow through more space.
4. **Opening Size:** The openings should be as large as possible to allow for greater airflow.
5. **Operation of Opening:** The openings should be fully adjustable, to change the amount of airflow as the need changes.
6. **Direction of Opening:** The openings should have adjustable louvers or panels to direct the wind into the opening.
7. **Skylight:** Skylights are very desirable for nighttime thermal comfort in houses to vent heated/warm air that rises, and to let us radiate heat to the cold sky.
8. **Windows:** Windows open to the sky and other relatively cold surfaces such as the woods, the sea, would improve thermal comfort on the same principle.
9. **Shading:** Let the sun shine on the building when heat is needed and shade the building when heat is not needed.

The following are strategies that should be considered to get the best performance from a building that incorporates natural ventilation strategies:

1. **Mechanical ventilation before mechanical air-conditioning:** With the fans positioned properly to remove the hot and humid air with little resistance on the airflow, they will use “one tenth the electrical energy consumption of mechanical air-conditioning systems”<sup>34</sup>
2. **Cool the building at night:** with the use of thermal mass, such as concrete or granite, this strategy will maintain cooler temperature through the day.
3. **Dehumidify vs. mechanical air conditioning:** “The typical air conditioning system spends about 80 percent of its capacity to cool and only 20 percent to dehumidify.”

Conventional vapor-compression cooling systems cool effectively but dehumidify inefficiently and imprecisely. Desiccant dehumidifiers employ materials with a high affinity for water vapor to attract and retain moisture from building ventilation air. Often the air in a conditioned space needs dehumidification with little or no cooling. Additionally, dry air is easier to cool and feels comfortable at higher temperatures. Thus desiccant dehumidification reduces the work of the cooling system, cutting energy use and operating costs. Using desiccant conditioning also allows the use of smaller, less costly conventional air conditioning systems because the latent load is being handled by the desiccant unit.”

Desiccants can also dry out the air used by conventional air conditioners, “eliminating the need to both dehumidify and cool the air” in the same air conditioning process, possibly saving energy.
Section B: Understanding Buildings with Natural Ventilation – Summer 2000 Tour

Progress has been made in the building industry throughout the world to better understand how to minimize energy consumption while designing modern buildings. However, much of the natural ventilation technology and understanding has not been able to have implementation here in the United States. In an effort to have some technology transfer, the trip to Europe was set up to meet with architects, engineers, and building managers concerning natural ventilation design and operational naturally ventilated buildings. The trip became a two-week expedition through Denmark, Germany, Belgium, the Netherlands, Scotland, and England, visiting about twenty naturally ventilated buildings. Simple philosophies and techniques were understood from the visits and discussions at each of the buildings visited.

In the effort of planning and organizing the trip, the most important and difficult part was finding buildings and people that we could meet to discuss the advances in natural ventilation. With a head start from work done by Daniel Arons on double skin facades here in the Building Technology program at MIT, contacts and buildings in Germany became available. Next, with the generosity of WindowMaster, we were able to set up a meeting and visits to five naturally ventilated buildings in Denmark. Beyond these important leads, a literature search was needed to find the other buildings. From this information, many of the contacts were willing to take some time to meet concerning their buildings or natural ventilation in general.

The intention of the trip is to then answer questions regarding energy use, cooling strategies, user comfort and problems that have been encountered in the operation or design of the building. Through the various types of buildings that we visited, many different high-tech and low-tech solutions were created to induce natural ventilation when useful. The following sections have examples of the different technologies:

- Solar Shading
- Operable Windows
- Window Placement
- Thermal Mass
- Building Zones
- Building Automation
- Double-skin Facade
- Atrium
- Chimney / Stack
- Number of People
- Floor Plan
- Landscape

For more detailed information on each of the buildings that were visited, please go to Appendix A.
Solar Shading

Solar Shading is a key feature that needs to be designed to allow natural ventilation to work properly. Every building that uses natural ventilation should have solar shading. Each building that we visited in Europe had solar shading to varying degrees. In general it was noticed that the most effective shading was external to the conditioned zone, although some had shading between windowpanes and yet others had shading in the conditioned zone.

The Sofiendal School is a good example of external shading to block the direct solar gains from entering the conditioned space. The south wall of the building was able to have numerous windows for both natural light and natural ventilation with the placement of the wooden shading structure to block the majority of the direct solar heat from entering the classroom.

In the RWE tower boardroom, the internal blinds are used in addition to a shading device on the roof for the skylight and the ceiling over the hallway around the perimeter. The internal blinds in the buildings on our tour, similar to the RWE tower, were not the only means of blocking out the solar heat gains. Typically the internal blinds were used
to keep out the diffuse solar light, while another shading device would keep the majority of the direct solar energy away from the conditioned space.

Victoria Insurance, Dusseldorf, Germany (blinds in double-skin fa"c"ade)

Victoria Insurance uses shades in the double-skin façade, as we saw in other double-skin façade buildings. The shade is used between the outer and inner glass of the façade to catch and reflect the solar heat gain before entering the conditioned space. The heat would then rise out of the façade when heat was not needed to enter the building.

Aston’s Administrative Building, Copenhagen, Denmark (blinds in window unit)

Aston’s new building is a good example of the blinds between two glass panes in one window. The blinds keep the direct solar radiation from entering the conditioned space. However, heat gain enters the conditioned space through the glass panes, which will have a higher temperature from solar heat gain of the air in the window cavity.
Operable Windows
Operable windows are vital for allowing air to move naturally between inside and outside. Through our visits, we found that there were primarily four kinds of windows being used for natural ventilation, as described with the building examples:

Commerzbank, Frankfurt, Germany
(Operable window in double-skin façade)

Commerzbank has a fixed outer façade, which allows air to rise through the façade of the building. Each office has the ability to open their interior window for airflow into the conditioned space.

Pearson Education’s Edinburgh Gate,
Harlow Town, England (Tilting window)

Edinburgh Gate has manual operable windows that tilt in and out for office space air movement and mechanically operated windows that tilt out at the top of the atrium space for public space air movement.
Main Tower has mechanically operated windows that push out away from the office space to allow air to move in from side, top, or bottom of the window depending on indoor and outdoor conditions. This type of window is able to interrupt the air that rises against the outer wall of the building, directing some into the occupied space.

The dormitory at Strathclyde University uses windows that open inward as a swinging door, allowing a large airflow area. Since these windows open in, they are unable to direct the wind into the building.
Window Placement
The placement of both operable and non-operable windows is important for both inducing airflow and solar shading effectiveness. Often it is best to place operable windows both near the ceiling and near the floor of the conditioned space. We found the following window placement types:

![WindowMaster Headquarters, Vedbaek, Denmark (operable skylight)](image)

The use of the operable skylight at WindowMaster Headquarters allows the hot air to rise out of the building. The skylight is placed in the hallway space, which is able to create air movement from each of the rooms connected to the hallway.

![Stadttor, Dusseldorf, Germany (windows at the top and bottom on the atrium)](image)

The Stadttor Dusseldorf places operable inlets and outlets at the top and bottom of each end of the large atrium space. This allows air to move through the space with a large wind or up and out of the space when the air is too warm.
The ABN Amro building uses small windows toward the top of each floor to create a small and fairly constant airflow of the hot air out of the building at the buildings perimeter. This setup is never able to create a large natural flush of air to remove heat from the occupied space, but could be used in combination with a pressurized building to push hot air out of the occupied space.
Thermal Mass
Thermal mass can be used with natural ventilation to moderate the room temperatures.

Each floor of the European Patent Office has the concrete reinforced overhang and outer wall except for the top floor of the low-rise section of the complex. The thermal mass has allowed the building to be operated with out air conditioning, except for the floor that does not have the thermal mass overhang and exterior wall. The thermal mass collects the solar heat gain, unlike a metal wall which conducts the heat into the occupied space.

The older section of this maternity hospital has a thick thermal mass construction, and is operated without air conditioning. The newer section was built with lighter weight construction, and uses multiple through wall air conditioning units to maintain comfort.
The British Research Establishment's Environmental Building uses a wavy ceiling to allow for increased thermal mass surface area to moderate the internal temperature. The increased surface area allows for more heat transfer to occur between the conditioned space and the ceiling. The waving ceiling was also helpful in reflecting more light off of a larger white surface.
Building Zones
The use of zones within a building can allow for the use of multiple conditioning strategies depending on occupants or use.

Commerzbank, Frankfurt, Germany

Commerzbank has atriums, offices and cafeteria as the three major zone types for the tower. The cafeteria is separately zoned due to both a different use type and schedule. The atrium is zoned as a moderate zone between the external and office climates.

University of Nottingham, Nottingham, England

The University of Nottingham complex is zoned based on use types, including the atrium, office spaces and lecture halls. The atrium space is intended to be a comfortable moderate zone as you enter the buildings.
Building Automation
Automation of openings and heating & cooling systems is useful in designs that use natural ventilation to guide the users habits.

Sofiendal School, Sofiendal, Denmark
(day and night automated windows)

The Sofiendal School has a full building management system that can operate the external windows day or night to create a comfortable internal temperature.

Commerzbank, Frankfurt, Germany
(Atrium large windows and cafeteria windows and blinds)

Commerzbank has a full building management system that controls the atrium windows as well as the cafeteria windows and blinds. The use of sensor allows the building management system to know what the internal and external conditions are.
The Stadttor has a building management system that operates the buildings blinds, public space windows, and internal temperatures. The occupants are allowed to override the system when the building reacts to the current conditions.

The Inland Revenue Service complex has its building management system raise and lower the opening to each of the stairwell stacks to induce airflow from the office space corridors.
Double-skin Facade
Double-skin facades moderate the extreme conditions for the occupied spaces. The conditions moderated include noise, wind, solar heat gain, and cold temperatures.

Victoria Insurance, Dusseldorf, Germany
(street level and high-rise double-skin façade)

The double-skin moderates the weather conditions and city noises for the offices at the lower levels, while diverting solar heat from entering the occupied office space.

Stadttor, Dusseldorf, Germany
(wide cavity high-rise double-skin façade)

The design of the inlet and outlet of the double-skin façade had its design optimized over a 2-year period that produced an estimated 300-400% greater airflow. The design went from straight opening to finally having louvers and an internal louver to direct the airflow smoothly into the façade cavity.
Atrium
An atrium is useful in natural ventilation designs to create both an open volume where air can move horizontally between spaces and vertically to move hot air away from the occupied space.

![Pearson Education's Edinburgh Gate, Harlow Town, England](image)

Edinburgh Gate has three atriums that extends from the first floor to above the top floor, allowing air to flow in through the office spaces from the exterior wall and then in to the atrium and finally the warm air will exit near the ceiling of the atrium.

![Stadttor, Dusseldorf, Germany](image)

The Stadttor Dusseldorf places operable inlets and outlets at the top and bottom of each end of the large atrium space. This allows air to move through the space with a large wind or up and out of the space when the air is too warm.
Commerzbank, Frankfurt, Germany
(zoned atriums, garden and office space)

The atrium spaces at Commerzbank extend up through 12 stories, allowing air to flow in through offices and garden spaces at the lower sections and the up and out through the top-level atrium garden.

Aston's Administrative Building, Copenhagen, Denmark
(atrium with skylight between office space)

Aston's Building has an atrium that runs through the center of the building allowing air to flow in through the office spaces from the exterior wall and then in to the atrium and with the warm air exiting from the skylight at the peak of the atrium.
Chimney / Stack

A chimney or stack is used in natural ventilation designs to create a tall vertical space that promotes hot air movement up and out of the occupied space.

University of Nottingham, Nottingham, England
(rotating wind sail over stacks)

The University of Nottingham complex has a series of ventilations stacks that help to move air in and out of the attached buildings. The wind sails are used to catch wind to create air movement into the building. The stack will work in low wind conditions to move the warm air up and out of the stack.

Building Research Establishment, Garston, Watford, England
(5 aluminum and glass block stacks)

The Building Research Establishment’s Environmental Building uses glass block and aluminum stacks to move warm air up and out of the office spaces.
Number of People
The design of a naturally ventilated building changes significantly based on the number of people that occupy the space.

The ING Bank Headquarters is an example of a building that was designed for natural ventilation with a low-density workspace. The building has since transitioned into high-density workspaces with more people and computers. This transition does not allow the building to operate with any natural ventilation at this time.

The RWE tower is an example of a building designed to house executive offices with low-density workspaces. With this setup, the tower has been able to maintain lower energy use than a comparable tower.
Floor Plan
The architectural layout of the building floor plan determines where the airflow paths are available for natural ventilation.

Pearson Education’s Edinburgh Gate, Harlow Town, England
(floor plan is parallel to airflow path)

Edinburgh Gate was the best example of how to use a floor plan to help create a flow path for natural ventilation. The office spaces were setup with the vertical elements, such as walls or bookshelves, placed parallel to the airflow. In addition, the doors for offices operated opposite of typical doors, as they are designed to stay open, unless they are specifically shut by the occupant, which allows air to move through the office and into the atrium space.
**Landscape**
The exterior landscape can be designed to help to minimize the solar loads on the building, lower the entering air temperature, and direct air flows into the buildings openings.

Pearson Education’s Edinburgh Gate, Harlow Town, England
(planting on roof level balcony)

Edinburgh Gate has plantings on the roof used as the balcony for the top level of the atrium. This use of plants helps to create a cooler roof surface and even do minimal shading of the glass.

Sainsbury Greenwich, Greenwich Peninsula, England
(Use of Earth Berm to maintain wall temperature)

Sainsbury Greenwich, an energy efficient supermarket, uses an earth embankment around the perimeter of the building to help maintain the temperature of the outer wall. This help to moderate the internal temperature with the ground temperature, which creates a cooling effect in the summer.
Section C: Understanding Buildings that use Natural Ventilation – Building Readings

**Single Sided Ventilation Approaches:**

Cambridge University, Math Science Building, UK: The building was built to allow natural ventilation and solar shading. The office space has three windows stacked on top of each other, with both top and bottom operable windows. Sensors are used to determine how much the windows open to create appropriate airflow into the offices. The upper window can be opened for nighttime cooling. The top and middle windows have blinds that are used to shade the interior space from the solar heat gains.<sup>38</sup>

**Double Skin Façade:**

Debis C1 Complex, Berlin, Germany: The use of a double-skin façade moderates the transfer of conditions between the interior and exterior. The low-rise and high-rise complex has a double-skin façade that "balances the difference between wind pressure and the interior air pressure"<sup>42</sup> to allow for the interior space to be ventilated naturally.

**Manual operation of windows in AC building:**

Computer Sciences Facility, York University, Toronto, Ontario, Canada: At the new computer sciences facility, occupants will be given instructions on when to keep their windows closed, and will be trusted not to undermine the mechanical system. This is different than many buildings, which use either a mechanical override or locks on the windows when air conditioning is in use.<sup>23</sup>
Building Management System Control:

Trendpark Neckarsulm, Neckarsulm, Germany: The design allows for natural ventilation to be used based on the building management system (BMS) settings and the interior and exterior conditions. The exterior temperature is calculated over 24 hours and used to determine how the BMS operates the building based on three climate concepts, the heating season, the cooling season, and a mixed season. Mechanical ventilation is used during winter, the heating season, whereas Natural Ventilation is used during mixed seasons, spring and fall. Solar shading can also be operated by the BMS, but the individuals can operate the blinds when they need to. 

Glass Atrium:

Reichstag, Berlin, Germany: This historic building was rebuilt with a design by Foster and Partners that includes natural ventilation through a glass dome. “The final design incorporates a new roof structure, which deflects controlled daylight into the Plenary Chamber below and also scoop out air as part of the system for natural ventilation.” Large air ducts let the fresh air into a ‘pressure floor’ with a minimum use of energy. The air moves into the occupied space, where the air heats up and moves up toward the glass dome, where the hot air moves out of the building. At the opening, a wind deflector helps to increase airflow through the building when wind is available.
Mechanically Assisted Natural Ventilation:

Bang & Olufsen, Struer, Denmark: This building using both mechanically operated windows and fans to assist natural ventilation. The air enters the building at each floor at the bottom of the office spaces. The air moves through the occupied space to move toward the outlet at the top of the three staircases. At the outlets, at the top of the staircase boost ventilators are used to assist the natural ventilation when large amounts of natural airflow is not possible. <37>

Natural Ventilation Showcase Building:

Velux, Trimbach, Switzerland: This building was renovated in 1992 with various types of ventilation. The building has "open architecture" which allows for stack ventilation between the multiple floors of the building, "providing a sufficiently strong force for ventilation." Sensors are used to understand the rain, temperature and wind to operate the attenuators. The building pays attention to security issues by having no automatically opened windows on the ground floor as well as secured windows in the basement. Occupants can manually operate the non-automated windows and the external shades. <24>
Residential Complex with Natural Ventilation in the United States:

Residential complex, EcoVillage, Ithaca, New York: In the new EcoVillage in Ithaca New York, residential units are design to optimize the ability to use natural ventilation. Natural ventilation is used to provide both comfort and health to indoor environments. Another goal for using natural ventilation was to save money in construction costs as well as long-term energy savings, by reducing the need for either mechanical ventilation or air conditioning. The complex considers the ventilation in three categories to serve three functions with different airflow needs. For indoor air quality, indoor air is replaced with outdoor air. For thermal comfort, “comfort ventilation” is used to maintain internal air temperatures for the comfort of the occupants. Third, nighttime cooling is used to cool the building through the night so the “building acts as a heat sink during the next day (nocturnal ventilative cooling).”

Convention Center Natural Ventilation:

David L. Lawrence Convention Center, Pittsburgh, Pennsylvania: This convention center in a large public space and is a 1.3 million square-foot building. The building was designed by Rafael Viñoly, and is scheduled to be complete in 2003, capable of using natural ventilation when outdoor conditions are appropriate. The large open areas, including the exhibit hall and circulation areas will be naturally ventilated throughout much of the year. The smaller spaces, including the meeting rooms will have cool air enter from openings along the building’s river and city ends. It is estimated that natural ventilation will save about 25 percent in energy costs over comparable buildings.
High-Rise Commercial Natural Ventilation:

Swiss Re, London, England: This design utilizes the building's glazing which wraps around a diagonally braced structure, rising 179.8m (590 feet) above a new public space surrounding its base to act as an acoustic buffer to the outside and provides natural ventilation and daylight. Each floor uses a floor plan that is rotated from the floor above and below to create voids at the edge of each floor to create a "spiral atria". This allows the building to push natural ventilation by "means of the large pressure differentials generated and natural air being drawn in at every floor via horizontal slots." Throughout the year, natural ventilation will assist the conditioning of the air, so that cooling and ventilation can be switched off. The goal of this is to create a "commercially sound" building with lower operating costs and desirable working space. Similar to the design for Commerzbank, the "atria are closed every six floors by gardens, which both control air movements and divide the building into fire compartments." <18>

New Natural Ventilation Office Design:

ING Group Headquarters, Amsterdam, The Netherlands: This new building will have office space for 400 people with 7500 m² of office space and 20,000 m² of total floor area. "Modern construction systems and natural materials" are used throughout the design. The building also has a transparent double-skin façade, which has windows that can be opened allowing natural ventilation to used to condition the office spaces. The building has also an air conditioning system that uses heat pumps for hot and cold storage in the soil to reduce the energy needed. The energy used to light the office spaces will also be reduced due to the ability to use daylight instead on electric lights. <22>
Chapter 3 Energy Analysis Studies
Section A: High Rise Residential in Shanghai, China

HOT CLIMATE HIGH RISE RESIDENTIAL ENERGY ANALYSIS

This research was conducted to determine the energy savings associated with different design aspects of high-rise residential buildings in Shanghai China. The high-rise building, as depicted above, tried to utilize shading techniques and other hot climate technologies to minimize the cooling energy use. This study was done in coordination with additional research looking at the architectural design, layout, and features for buildings in China. There is motivation to minimize the energy use of mechanical equipment by increasing the architectural detail standards, including proper use of insulation, ventilation, and shading. While this research is focused on overall heating and cooling energy use, other research is being conducted to determine advancements in shading technologies and ventilation standards. The energy simulation research is focusing on energy use and cost savings with increased building standards and attention to specific energy efficient details, including ventilation and window shading.

DESCRIPTION OF BUILDING AND SIMULATION METHODOLOGY

The energy simulations have been created through using a DOE-2 building energy simulation program that uses the DOE-2.1E simulation engine. The simulation accounts for the building geometry, materials, equipment, occupants, surrounding and other details that effect energy usage. The program uses hourly weather data for Shanghai to determine the energy usage for each given hour for the specified condition of the building. The hourly weather data used in this study was obtained from Lawrence Berkeley National Laboratory, and was compared to another weather file obtained from www.doe2.com, giving increased confidence for the accuracy of the weather file. The hourly outdoor dry-bulb temperatures for Shanghai are plotted below. Various hourly weather data was examined to better understand the resulting energy usage, including abnormal or extreme weather days.
Figure 3a-1. Hourly outdoor dry-bulb temperatures for Shanghai

The results will be shown in a series of two types of simulations. The first set, called "Baseline Parametric Simulations" includes only single feature upgrades versus the baseline case, as described in Figure 3a-2. The second set, called "Combined Feature Simulations" includes multiple feature upgrades to determine if synergistic effects can occur from proper design.

<table>
<thead>
<tr>
<th>Building Component</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor Area</td>
<td>2 story, 7 meter x 15 meter</td>
</tr>
<tr>
<td>Wall Type</td>
<td>30.4 cm concrete, no insulation</td>
</tr>
<tr>
<td>Window Type</td>
<td>Single Pane Aluminum Frame</td>
</tr>
<tr>
<td>Window Area</td>
<td>33.3% Window to Wall Area</td>
</tr>
<tr>
<td>Overhang Type</td>
<td>No Overhang</td>
</tr>
<tr>
<td>Electric Heat Pump</td>
<td>10 SEER / 7.8 HSPF</td>
</tr>
<tr>
<td>Heating Setpoint</td>
<td>20 Celsius</td>
</tr>
<tr>
<td>Cooling Setpoint</td>
<td>24 Celsius</td>
</tr>
<tr>
<td>Ventilation</td>
<td>Minimum for IAQ</td>
</tr>
</tbody>
</table>

Figure 3a-2. Baseline feature specification

The baseline case is a duplex unit with only North and South facing exterior walls. This was determined to be a typical case, and was used at the starting point for the energy
Simulation. Since the unit modeled has only North and South facing walls, the East and West facing walls were modeled as adiabatic. The ceiling and floor were also modeled as adiabatic since a typical unit in a high-rise building is not a top floor or ground floor unit.

**BASELINE PARAMETRIC SIMULATIONS**

The initial simulation completed was the baseline case as explained in Figure 3a-2. This baseline case is used as a basis for comparing various upgrade possibilities in the building design. The first set of simulations created as a comparison to the baseline simulation, described as "Building Features", upgrades the buildings design features, including the windows or walls. The second set, "Detail Specifications", upgrades the components designed within each unit, including the HVAC equipment.

In the "Building Features" set of upgrades, the following upgrade simulations were created, and are shown in Figure 3a-3:

- ½ meter overhang on the south façade of the building at each floor,
- 1 meter overhang on the south façade of the building at each floor,
- no absorptivity on the exterior walls (ivy or other wall curtain on exterior wall),
- 50% window to wall area ratio (WWA),
- 75% window to wall area ratio (WWA),
- Concrete Wall ½ the original thickness,
- Concrete Wall ½ the original thickness plus 1" Styrofoam insulation,
- Concrete Wall ½ the original thickness plus 2" Styrofoam insulation.

![Yearly Energy Consumption per Typical Residential Unit](image)

**Yearly Energy Consumption per Typical Residential Unit**

**Baseline Parametric Simulations - Building Features**

<table>
<thead>
<tr>
<th>Upgrade</th>
<th>Heat (MWh)</th>
<th>Cool (MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>6.1</td>
<td>5.7</td>
</tr>
<tr>
<td>Overhang ½ m.</td>
<td>5.4</td>
<td>4.5</td>
</tr>
<tr>
<td>Overhang 1 m.</td>
<td>4.3</td>
<td>4.2</td>
</tr>
<tr>
<td>No Wall Absorptivity</td>
<td>3.4</td>
<td>3.2</td>
</tr>
<tr>
<td>50% Window to Wall Area</td>
<td>6.1</td>
<td>6.9</td>
</tr>
<tr>
<td>75% Window to Wall Area</td>
<td>3.9</td>
<td>4.1</td>
</tr>
<tr>
<td>Concrete Wall + R4</td>
<td>3.2</td>
<td>3.4</td>
</tr>
<tr>
<td>Concrete Wall + R8</td>
<td>2.6</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Dean
In the “Detail Specifications” set of upgrades, the following simulations were created, and are shown in Figure 3a-4:

- Standard double pane window with clear glass,
- High performance double pane window (low-E, vinyl frames, low infiltration),
- Night time insulation on windows, such as curtains,
- Ventilation at 5 air changes per hour (ach) from April 1 through May 31 and from September 1 through October 31,
- Ventilation at 10 ach, during the same moderate seasons,
- Heating season nighttime setback on the thermostat from 20 °C to 15.6 °C during the night hours from 10 PM to 6 AM,
- Cooling season setup to 26.7 °C throughout the entire season,
- Cooling season setup to 29.4 °C throughout the entire season.

In addition to looking at the energy usage, it is often easier to understand the simulations when you convert them into money savings that can occur. In Figures 3a-5
and 3a-6, the operating cost comparisons are done for the Building Feature and Detail Specification sets of runs respectively. The cost was calculated per residential unit based on an electric rate of 6 cents per kilowatt-hour (kWh). Through this you will see that as much as one third of the energy cost can be saved by single upgrades alone, such as changing the cooling set point to 29.4 °C.

![Yearly Energy Cost per Typical Residential Unit](image)

**Figure 3a-5.** Cost savings for building feature upgrades versus the baseline case.
Figure 3a-6. Cost savings for detail specification upgrades versus the baseline case.

**COMBINED FEATURE SIMULATIONS**

The next series of simulations were created to determine how upgraded features work together for overall energy savings. First, the information gathered from the baseline parametric runs was examined to determine which upgrades were the best and in other case to determine which were most feasible. The information obtained through the simulation of multiple upgrades versus the baseline case is displayed in Figures 3a-7 and 3a-8.

The first simulation shown has taken each of the best upgrades together to determine that as much as 67% savings can be gained from these design features alone. The second simulation took a more feasible approach, by using upgrades that may be more cost effective in the construction process. This method still proved to be quite effective by creating a 53% savings compared to the baseline case. The following three simulations increased the window area to 50% WWA, to allow more architectural flexibility, and were offset with window upgrades. The first of these three runs has night insulation and an overhang, with a standard double pane window, while the second case does not include the overhang, and the third does not include the overhang or the night insulation. These runs best show how the heating and cooling loads are effected...
by solar heat gain and window conduction. This also shows that windows are an important design feature in this climate. The final simulations explored the effects of the heating and cooling set points with the incorporation of ventilation at 5 ach. The results and description of each can be seen in Figure 3a-7.

Figure 3a-7. Energy savings through the combination of feature upgrades.
The energy data from the simulations in this section were also converted into cost data. Again, the cost was calculated per residential unit based on an electric rate of 6 cents per kilowatt-hour (kWh).

![Yearly Energy Cost per Typical Residential Unit Combined Feature Simulations](chart.png)

**Figure 3a-8.** Cost savings through the combination of feature upgrades.

**HOT CLIMATE HIGH-RISE RESIDENTIAL CONCLUSION**

The simulation in this research shows that significant energy savings can be secured through proper design of both the building features and the detail components. The cooling load can most significantly be decreased through the use of windows shading and ventilation. Helpful window components to minimize solar gain include a shading device for the summer sun or a lower solar heat gain coefficient on the glass of the window. To significantly help the occupant lower the heating and cooling loads, the building design should incorporate technology that allows the user to have ventilation into the space. In addition, the equipment should promote the use of higher summer set points and lower winter set points. Promoting these uses alone will allow the energy savings between 30% and 50%, while also increasing space comfort for the occupant.
Section B: Residential Development in Shenzhen, China

HOT CLIMATE RESIDENTIAL DEVELOPMENT ENERGY ANALYSIS

This research was conducted to determine the energy savings associated with different design aspects of residential buildings in Shenzhen, China. This study has been done in coordination with additional research looking at the architectural design, layout, and features for buildings in China. There is motivation to minimize the energy use of mechanical equipment by increasing the architectural detail standards, including proper use of insulation, ventilation, and shading. The energy simulation research is focusing on energy use and cost savings with increased building standards and attention to energy efficient details, such as shading, ventilation and building layout.

DESCRIPTION OF BUILDING AND SIMULATION METHODOLOGY

The energy simulations have been created through using a DOE-2 building energy simulation program that uses the DOE-2.1E simulation engine. The simulation accounts for the building geometry, materials, equipment, occupants, surrounding and other details that effect energy usage. The program also uses hourly weather data for Hong Kong to determine the energy usage for each given hour for the specified condition of the building. The hourly weather data for Hong Kong was used in this study since it was the closest major city weather data available in format used by DOE-2. In Figure 1, the hourly outdoor dry-bulb temperatures vs. humidity for Hong Kong are plotted. The dry-bulb temperature and other hourly weather data was obtained from the
weather file to better understand the resulting energy usage, including abnormal or extreme weather days.

By examining the temperature vs. humidity chart, there are significant hours throughout the year that are not within the comfort zone for people, with either still air or an additional 2 m/s of air movement. This does not allow for significant usage of natural ventilation throughout the year. It has been determined that ventilation can be used in the late fall, winter, and early spring. Energy simulations in DOE-2 support this, and provide additional data to quantify the use of natural ventilation during these seasons.

![Humidity vs. Temperature](image)

**Figure 3b-1.** Hourly outdoor dry-bulb temperatures vs. humidity for Hong Kong, with each point representing one hour of the year. Comfort zone is based on ASHRAE comfort conditions; extended climate zone with 2 m/s airflow is based on B. Givoni<sup>19</sup>.

The simulations will be shown in a series of two types of simulations. The first set, called "Single Energy Efficient Measures" includes only single feature upgrades versus the baseline case, which is described in Figure 3b-2. The second set, called "Multiple Energy Efficient Measures" includes multiple feature upgrades to determine if synergistic effects can occur from proper design.
<table>
<thead>
<tr>
<th>Building Component</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor Area</td>
<td>2 story, 7 meter x 15 meter</td>
</tr>
<tr>
<td>Orientation</td>
<td>North/South facing facades</td>
</tr>
<tr>
<td>Window Type</td>
<td>Single Pane Aluminum Frame</td>
</tr>
<tr>
<td>Window Area</td>
<td>50% Window to Wall Area</td>
</tr>
<tr>
<td>Overhang Type</td>
<td>No Overhang</td>
</tr>
<tr>
<td>Electric Heat Pump</td>
<td>10 SEER / 7.8 HSPF</td>
</tr>
<tr>
<td>Heating Setpoint</td>
<td>20 Celsius</td>
</tr>
<tr>
<td>Cooling Setpoint</td>
<td>24 Celsius</td>
</tr>
<tr>
<td>Ventilation</td>
<td>No Ventilation</td>
</tr>
</tbody>
</table>

**Figure 3b-2.** Baseline feature specification

The baseline case that is being modeled is a duplex unit with only North and South facing exterior walls. This was then compared to energy calculations for units with West and East facing walls. The exterior walls we modeled with concrete block walls, while the facades without the windows were modeled as adiabatic, and assumed to be between two other units. The ceiling and floor were also modeled as adiabatic since a typical unit in these residential buildings is not a top floor or ground floor unit.

**SINGLE ENERGY EFFICIENT MEASURE SIMULATIONS**

The initial simulation run completed was the baseline case as explained in Figure 3b-2. In the “Single Energy Efficient Measures” set of upgrades, the following upgrade simulations were created, and are shown in Figure 3b-3:

A. Base Case (as above)
B. Window Shading Coefficient 0.4 (from 0.8)
C. 25% window to wall area ratio (WWA)
D. 1 meter Overhang (North and South)
E. 1 meter Overhang (South windows)
F. 1/2 meter Overhang (South windows)
G. Winter, Spring and Fall Ventilation at 10 ach
H. Minimal leaks: Infiltration at 0.35 ach (from 0.75 ach)
I. Vinyl window frame (from aluminum)
J. 6 cm wall insulation
K. Wall absorptivity 0.50
L. Wall absorptivity 0.95
Figure 3b-3. Energy use for single feature upgrades vs. the North/South baseline case.

In Figure 3b-3, it can be noted that the largest energy load is the cooling load. More specifically, it was found that the largest cooling load is created from solar energy gain through the windows. With upgrades to the windows or overhang components, more than 30% savings can be reached. Additionally, much of these heat gains can also be ventilated out of the residence to create almost 25% energy savings.

Additional simulations were also completed to better understand the effects of certain upgrades to building standards. A study was done to determine the effects of having an East/West orientation to the residential unit. The next study done was to determine the benefits of ventilation throughout the year. Then last study done was to determine the effectiveness of insulation in the ceiling of the top units.
In the East/West orientation study the following upgrade simulations were created, and are shown in Figure 3b-4:

A. Base Case (as above except orientation East/West)
B. Window Orientation North and South only
C. Window Shading Coefficient 0.4 (from 0.8)
D. 25% window to wall area ratio (WWA)
E. 1 meter Overhang (West only)
F. 1 meter Overhang (East and West)
G. 1/2 meter Overhang (East and West)
H. 6 cm wall insulation

![Energy use for single feature upgrades vs. the East / West baseline case.](Image)

**Figure 3b-4.** Energy use for single feature upgrades vs. the East / West baseline case.

In Figure 3b-4, it should be noted that approximately 15% energy savings occurs from orienting window North or South versus East or West. Additionally, it is important to have overhangs on both the East and West windows. The other upgrades energy savings are similar to those simulated in the North/South orientation.

In the ventilation study the first set of simulations that were created were to determine the energy savings on a monthly basis. Figure 3b-5 shows energy savings for all months except for the hottest months, which showed no savings. Figure 3b-6 shows the energy savings for combining ventilation savings from multiple months.
In Figure 3b-5, it should be noted that most of the energy savings comes from ventilating the residential units throughout the day, when the solar gains are increasing the cooling load. Additionally, it can be seen that there is very minimal opportunity to ventilate during the months of June, July, August, and September. This information was used to create the ventilation strategies shown in Figure 3b-6.
Figure 3b-6. The energy savings for ventilation strategies.

Figure 3b-6 illustrates the importance of a good ventilation strategy. It is interesting to compare the 5% cooling energy savings simulation, which uses 10 air changes per hour in the night time of the spring and fall (F,M,O,N) and the final ventilation strategy, which can save as much as 30% of the cooling energy. By ventilating the hot internal air from the residences through most of the year, less cooling needs to be done with an air conditioner.

MULTIPLE ENERGY EFFICIENT MEASURE SIMULATIONS

The next type of simulations were created to determine how upgraded features work together for overall energy savings. First the information gathered from the single energy efficient measure runs was examined to determine which upgrades were the best and in other case to determine which were most feasible. The information obtained through the simulation of multiple upgrades versus the baseline case are displayed in Figures 3b-8.
Figure 3b-7. Energy savings through the combination of feature upgrades.

In Figure 3b-7, it can be seen with just 4 simple upgrades to the building standards, more than 40% savings can be obtained. Working with the needs of the residence users, additional savings can occur without inconveniencing their lifestyles, by designing to be more sustainable.

In cooperation with Sephir Hamilton, a fellow student in the Building Technology program, we were able to create recommendations for the developers of the complex in Shenzhen China. The information in the following tables is based on the research in this chapter, and additional research by Mr. Hamilton.21
<table>
<thead>
<tr>
<th>Building Design Features (for spaces primarily facing North and South)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Windows</strong></td>
</tr>
<tr>
<td>North Overhang: 10% of window height; Fin: 10% of window width; Solar Heat Gain Coefficient &lt; 0.8 Clear single-pane window; (vinyl frame if possible)</td>
</tr>
<tr>
<td>South Overhang: 20% of window height; Fin: 10% of window width; Solar Heat Gain Coefficient &lt; 0.8 Clear single-pane window; (vinyl frame if possible)</td>
</tr>
<tr>
<td>Noise Control Tightly sealed windows (double-pane, non-operable if possible) on walls adjacent to railroad.</td>
</tr>
<tr>
<td><strong>Walls</strong></td>
</tr>
<tr>
<td>Insulation Block wall plus 6 cm. (R=1.5 or greater) of insulation on west facing exterior walls.</td>
</tr>
<tr>
<td>Noise Control Increase mass of walls adjacent to railroad by filling block wall cavities with dense concrete.</td>
</tr>
<tr>
<td><strong>Infiltration</strong></td>
</tr>
<tr>
<td>Blower door test (Random sample units) Less than 0.35 air changes per hour (fresh air by natural or mechanical ventilation). All joints and cracks should be sealed well.</td>
</tr>
<tr>
<td><strong>Roof</strong></td>
</tr>
<tr>
<td>Insulation Have at least 14 cm. (R=3.67) of typical fiberglass insulation or comparable insulation rating inside weather barrier. This will keep the top floor units from being too hot in the summer.</td>
</tr>
<tr>
<td><strong>Door</strong></td>
</tr>
<tr>
<td>Noise Control Exterior door adjacent to railroad should be heavy, such as metal with foam core or solid wood and should have gaskets and weather stripping to minimize infiltration of air or noise.</td>
</tr>
<tr>
<td><strong>Building Equipment Features</strong></td>
</tr>
<tr>
<td><strong>Cooling</strong></td>
</tr>
<tr>
<td>Air Conditioning 3 COP minimum, plus 0.3 COP each time the upgrade costs less than 1500 yuan. (example: add 0.9 COP [3.9 COP total] if cost of upgrade is less than 4500 yuan; add 1.2 COP if &lt; 6000 yuan)</td>
</tr>
<tr>
<td><strong>Ventilation</strong></td>
</tr>
<tr>
<td>Off peak ventilation Closable through-wall exhaust fan (ensure that they are properly sealed to have minimal infiltration when ventilation is not in use). For top floor units the exhaust fan should be placed near the roof.</td>
</tr>
<tr>
<td><strong>Thermostat</strong></td>
</tr>
<tr>
<td>Programmable Digital Clock Thermostat Install a programmable digital clock thermostat that controls the air-conditioner. Install a thermostat that reads indoor and outdoor temperatures.</td>
</tr>
<tr>
<td><strong>Hot Water</strong></td>
</tr>
<tr>
<td>Solar Collector Significant energy can be collected from the sun to heat the water used for bathing and washing.</td>
</tr>
</tbody>
</table>

Figure 3b-8. Residential units primarily facing North and South
<table>
<thead>
<tr>
<th>Building Design Features (for spaces primarily facing East and West)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Windows</strong></td>
</tr>
<tr>
<td>East and West with overhang</td>
</tr>
<tr>
<td>East and West no overhang</td>
</tr>
<tr>
<td>Noise Control</td>
</tr>
<tr>
<td><strong>Walls</strong></td>
</tr>
<tr>
<td>Insulation</td>
</tr>
<tr>
<td>Noise Control</td>
</tr>
<tr>
<td><strong>Infiltration</strong></td>
</tr>
<tr>
<td>Blower door test (Random sample units)</td>
</tr>
<tr>
<td><strong>Roof</strong></td>
</tr>
<tr>
<td>Insulation</td>
</tr>
<tr>
<td><strong>Door</strong></td>
</tr>
<tr>
<td>Noise Control</td>
</tr>
<tr>
<td><strong>Building Equipment Features</strong></td>
</tr>
<tr>
<td><strong>Cooling</strong></td>
</tr>
<tr>
<td>Air Conditioning</td>
</tr>
<tr>
<td><strong>Ventilation</strong></td>
</tr>
<tr>
<td>Off peak ventilation</td>
</tr>
<tr>
<td><strong>Thermostat</strong></td>
</tr>
<tr>
<td>Programmable Digital Clock Thermostat</td>
</tr>
<tr>
<td><strong>Hot Water</strong></td>
</tr>
<tr>
<td>Solar Collector</td>
</tr>
</tbody>
</table>

Figure 3b-9. Residential units primarily facing East and West
### Table

<table>
<thead>
<tr>
<th></th>
<th>KWh (annually)</th>
<th>% savings</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Base Case</strong></td>
<td>4500 - 5200</td>
<td>--</td>
</tr>
<tr>
<td><strong>3 Star Recommendations</strong></td>
<td>~2700</td>
<td>40-50%</td>
</tr>
<tr>
<td><strong>1, 2, &amp; 3 Star</strong></td>
<td>1500-1800</td>
<td>60-70%</td>
</tr>
</tbody>
</table>

Figure 3b-10. Possible savings based on recommended upgrades.

### Diagram

**Shenzhen Single Story Residence**

**Yearly Heating and Cooling Energy Usage**

Figure 3b-11. Energy savings for the recommended upgrades.

### HOT CLIMATE RESIDENTIAL DEVELOPMENT CONCLUSION

By examining the simulation in this research, it can be seen that significant energy savings can be secured through proper design of the building features. The cooling load can most significantly be decreased through the use of upgraded window components. Helpful window components include a shading device or overhang for the summer sun or a lower solar heat gain coefficient on the glass of the window, such as tinted or coated windows. Ventilation of the spaces, when used properly also has significant energy savings. In addition, the equipment should promote the use of higher summer temperature set points and lower winter temperature set points. Promoting these uses alone will allow significant energy savings, while also increasing space comfort for the occupant.
Section C: Analysis of Residential Dormitory Design at MIT

Prior to creating the natural ventilation analysis tool, the dormitory was analyzed in 4 separate cases to better understand the performance capabilities of the building. The first, part of the Building Technology Seminar, allowed Camille Allocca and I to team up to give an evaluation of the heating and cooling systems for the proposed building. Second, in October 1999, we attempted to analyze the effectiveness of ventilation with the energy program DOE-2. Also in October 1999, I used the tool Solar 5 to model different ventilation and cooling possibilities. Starting in December 1999, more focused research started on the natural ventilation and thermal mass effects on the design of the dormitory, using a tool created for this research.

In the first attempt to understand how the design by Stephen Holl would fulfill its attempt at being a sustainable design, Ms. Allocca and I, tried to understand the energy system issues. Additionally we looked at the design on a whole building approach to create questions that would help to move the design forward.

PART 1: Heating and Cooling Energy Issues

The significance of sustainable design can be seen in the proposed addition of a new 350 bed Student Dormitory in Cambridge, Massachusetts. A central area of focus in this new design has been to incorporate techniques that will reduce resource and energy consumption. The utilization of energy in the proposed design was analyzed by focusing on several contributing factors: (1) lowering energy consumption, (2) cost effectiveness, (3) climate and environment effects, and (4) renewable resources. This report analyzes both the heating and cooling processes, as well as the controls and sensors throughout the building design. An evaluation of the proposed energy systems as well as other components of the building design should help bring the design phase through a critical discussion phase.
Heating

In order to reduce energy consumption in the dormitory, Steven Holl has proposed a radiant slab heating system throughout each floor of the building. The dormitory floors serve as a thermal mass, collecting and storing heat provided by both the radiant heating system and solar heat gain. The presence of thermal mass works well with the proposed natural ventilation system by moderating temperature swings resulting from sudden peaks in solar heat gains.

Heating Equipment

The thermal mass storage of solar heat cannot meet the demands of the winter climate in Boston, since stored energy would be needed to provide heat overnight and during cloudy weather. Therefore radiant slab heating will be used in combination with the thermal mass and solar heat gain as the heating source of the dormitory. Radiant slab heating uses plastic, rubber or copper pipes embedded in a concrete floor to circulate heated water throughout the zones that need additional heating. Radiant slab heating operates effectively at relatively low temperatures. There is also an acoustic benefit to choosing this quiet form of heating, which is important in its application for student’s dormitory rooms. Details concerning the floor coverings in the student’s rooms are unknown. It is necessary for there to be minimal, floor covering so that the upward heat transfer from both the radiant slab heating and thermal mass can be effective.

Heating Energy Source

The proposed source of heated water for the radiant slab system is the existing source of steam that is currently created by the cogeneration plant, which produces electricity, steam, and chilled water for other uses around the MIT campus. Although campus steam may seem like an easily accessible and logical backup source, it may not be the most energy efficient or best suitable source for radiant slab heating. For this report, we are not able to determine the cost effectiveness or efficiency of the campus cogeneration plant, although we do recommend examining the following energy sources compared to current campus energy. Geothermal heat pumps work with the environment by absorbing renewable non-polluting solar thermal energy stored in the earth and ground water while using that energy to heat and cool a building. Unlike the large temperature drop of a Boston winter, earth temperatures are fairly uniform throughout the year allowing geothermal heat pumps to operate efficiently at a constant even temperature in this climate. Although geothermal heat pumps use a fair amount of electricity to circulate the water and run the compressor, they still cost less to operate than traditionally fueled systems. Geothermal heat pumps also require less space for heating and cooling since all equipment is stored inside the building or underground.
Heat Zoning

Another issue concerning radiant slab heating, which is mentioned but not discussed in the proposal, is zoning according to different façade exposures. One option is to zone each student’s dorm room. However, cost becomes a primary concern for this option. Another option is to create zones according to rooms with similar solar gain. If a multiple of rooms have the same solar gain, one thermostat should suffice to control those rooms as a separate zone. It is important to remember that each zone adds to the total cost, but may also be necessary to conserve energy.

Cooling

The cooling system that is proposed for the new dormitory is not fully described or designed. The initial discussion includes use of cooling in the public spaces on the first floor only, due to the natural ventilation design, as well as Cambridge’s cool climate. The proposed energy source for cooling the first floor of the sponge building is the existing source of chilled water that is currently created by the Cogeneration Plant, which produces electricity, steam, and chilled water for other uses around the MIT campus. The cost effectiveness and efficiency of the campus chilled water needs to be compared to additional sources of energy that can be used on the site.

Cooling Equipment

The exclusion of equipment specifications from the preliminary approach and schematic designs allows us to suggest possible opportunities for use of advanced equipment for the cooling system. Without focusing on a specific energy source for equipment, there are general equipment needs that can be met with better design and specification. The first major concern is the sizing of the system’s cooling capacity, to meet both initial cost and standard operation efficiency levels. Since summer is a short season and the function of the space is public, there is a potential to have a large deviation between an average cooling load and the peak summer cooling load, which systems are often sized to meet. A recommendation that would increase the average operating efficiency is to use of multiple smaller cooling systems, one that runs at a maximum efficiency for the average summer load. The cooling equipment is one of the applications that should use variable speed drive fans to allow for variable airflows, as the cooling loads vary.

Cooling Energy Source

The proposed energy source for cooling the first floor of the sponge building is the existing chilled water that is already being created for other uses around the MIT campus by the cogeneration plant. The cost effectiveness and efficiency of the campus chilled water needs to be compared to additional sources of energy that can be used on the site. Additional forms of energy that need to be considered include fuel cells, photovoltaic cells, and geothermal heat pump. Fuel cells are currently in use in many large buildings, and are between 40 and 50% efficient in the conversion of energy, as opposed to about 30% for the most efficient combustion engines. Photovoltaic cells...
used in solar arrays, should also be considered since it is renewable and generally available for use on the summer days when cooling is most needed. A third approach to provide cooling would be to use the relatively cool ground temperatures in the summer through the use of the geothermal heat pump, as explained in the heating energy source section in this report.

Controls & Sensors

The exclusion of specification for the controls and sensors leaves an opening for investigation into the true needs for the Cambridge climate and the MIT community. This building should incorporate technologies to not only increase efficiency, but also adaptability and ease of use. Programmable thermostats, which are now a popular control in buildings, should in some form be used for controlling the cooling of the public spaces as well as the heating zones, to minimize energy use, while increasing comfort. A specific technology that works well with the natural ventilation design is an indoor and outdoor thermostat that determines when outdoor conditions can help to increase indoor comfort. Additionally, similar to occupancy sensors for lighting, a setback occupancy sensor could be directly linked to the cooling thermostat to allow the room to heat up to a semi-comfortable temperature while not occupied.

Other Building Technology Issues

- Landscape: Use of landscape to minimize both direct and reflective solar heat gain on the south facade. Possibilities include both sidewalk trees and wall ivy.
- Sound vs. Lung Ventilation: When ventilation has more airflow in the building, sound flow is also at a maximum. Possible use of white noise to counter the noise heard through the openings to allow maximum ventilation openings.
- Wind tunneling: With open ventilation, will there be tunneling sounds that are created from air movement through the lungs or other passages?
- Air fans at the skylights: In the summer it is best to push out the hot air, which is created in the skylight of the lungs. In the winter, it would be more efficient to circulate the daytime hot air back to the first Solar UV Gain.
- Humidity vs. Lung and Natural Ventilation: the summer has the most humid air and is also the time when ventilation is needed most. Measures should be taken to minimize the amount of humidity that enters the building as well as the stagnation of humidity in any portion of the building.

Heating and Cooling Concluding Recommendations

The use of advanced building technologies in a new age dormitory will make for both a sustainable and livable environment. Additional energy sources such as geothermal, fuel cell, and photovoltaic cells should all be considered to power the heating and cooling systems. Advanced controls and sensors should also be used to maximize the use of the energy source that is used, as well as to meet the needs of the students and other that will live in the building.
PART 2: Analysis of Natural Ventilation with DOE-2

In the second attempt to understand the design of the dormitory of 2001, DOE-2 was used to analyze a portion of the building. In this analysis however, it was noticed that DOE-2 has some shortcomings when it tries to analyze the behavior of the building with the various natural ventilation strategies that we wanted to compare. This analysis was helpful to understand what a typical designer was capable of understanding from DOE-2 concerning the behavior of natural ventilation. This form of research was not continued due to the lack of confidence in the output from the initial analysis.
PART 3: Energy Simulation Using Solar 5

In an attempt to better understand the design implications for the Residence 2001
dormitory rooms, Solar 5, an energy and day lighting design tool, was used. This tool
was used to run 10 separate design cases on the same dormitory room. The goal of
these simulations was to determine whether any design would keep the occupants
comfortable without vapor compression air conditioning. The room that I selected is a
single person, 135 SF, south facing room, since particular attention is needed for the
design of the rooms that have the most solar heat gain in the summer, here on the MIT
campus in Cambridge Massachusetts.

The first design, the “base case”, was an attempt to simulate the current design of the
room, with the inclusion of cooling mechanical ventilation at 6 air changes per hour
(ach) maximum. With this first simulation it was found that the peak temperature in this
room would be around 78.2 degrees Fahrenheit (*F). Cases A-D are sequential
simulations building on each other, and the remainder of the simulations are noted from
which simulation they are building on.

- Case A was used to determine the effect of the size of the windows, and was a
  simulation of six, two foot nine inch square windows, instead of nine, two foot two
  inch square windows. Due to the angle of the summer sun, the increased size in
  individual window allowed more summer solar heat gain to enter the room, and
  brought the peak temperature up to 79.96 *F.
- Case B has changed window properties, with a lower U Value, and slightly higher
  shading coefficient. This also let more solar heat gain into the room, and
  increased the peak temperature to 80.18 *F.
- Case C used increased mechanical ventilation to 10 cooling ach, which brought
  the peak temperature back down near the base case, at 78.51 *F.
- Case D was simply used to look at the effect of heating settings, and did not
  change the cooling peak or average temperature.
- Case E, used the base case, and was designed with only 6 windows instead of 9
  windows, and increased cooling ventilation to 8 ach. In this case, I received the
  lowest peak temperature of 76.07, showing the importance of both the ventilation
  and the number of windows.

The final four simulations were done without mechanical ventilation, to determine if the
room can remain in a comfortable zone for the occupant.

- In simulation case F, the base case was the starting point, but this time with no
  mechanical ventilation, which had a dramatic effect on the peak temperature,
  raising it up to 91.48 *F.
- For case G, case E was the starting point, but again no mechanical ventilation,
  which was only slightly more comfortable than case F, with a peak temperature
  of 91.13 *F.
The final two cases used only 4 windows, with a very low shading coefficient of 0.2.

- Case H also used only natural ventilation, with no heating, the peak temperature was lower at 86.33 °F, but not as low as any of the mechanical ventilation simulations.
- The last case, case I, used natural ventilation and heating, with no mechanical ventilation, which was slightly higher than case H, with a peak temperature of 87.66 °F.

Please look at the following chart, showing a comfort line at approximately 78.5 °F and the 6 runs with mechanical ventilation, followed by the final four runs with only natural ventilation:

![Cooling Season Peak and Average Temperatures](chart.png)

**Figure 3c-1.** The energy use for different room strategies.

The following is a summary of upgrades shown in Figure 1:
- **Base Case.** 9 windows and 6 air changes per hour
- **Case A.** 6 windows instead of 9 windows
- **Case B.** Lower window U-value & higher window SHGC
- **Case C.** Mechanical ventilation of 10 air changes per hour
- **Case D.** Change in heating set point
- **Case E.** 6 windows and 8 air changes per hour
- **Case F.** No mechanical ventilation
- **Case G.** 6 windows and no mechanical ventilation
- **Case H.** 4 windows, no mechanical ventilation, and no heating
- **Case I.** 4 windows, no mechanical ventilation, and with heating
Solar 5 Analysis Conclusion

Through this analysis it was determined that without mechanical ventilation the students rooms in Residence 2001 will not be comfortable through the hot summer days. A major driving force is the size of the windows glass area and the solar gain that will occur with more glass area. Beyond the windows, it is recommended that increased mechanical ventilation be used during the nighttime cooling hours to minimize the morning temperature in the student’s room. Through the use of Solar 5, it is determined that the student’s room can be comfortable throughout the year without vapor compression air conditioning, but does need mechanical ventilation to assist the natural ventilation.
PART 4: Analysis of Natural Ventilation with the Natural Ventilation Analysis Tool

Through the development of the Natural Ventilation Analysis Tool, described in Chapter 4, we created building simulations for the new dormitory, so that we could understand how the design of the building could be improved. The early analysis using the Excel version of the Natural Ventilation Analysis Tool, the alpha version, began in December of 1999. Using the hourly weather data and room condition calculations, we first look to understand how the room conditions were behaving through the hot summer months.

For this simulation, room conditions were simplified to get an initial understanding of the room's reaction to natural airflow. The room has two 4 square foot windows with a 6-foot height between the windows. The room also has 750 watts of heat gain for the 1800 cubic foot volume student residence. The windows are operable for every hour, and there is no mechanical assistance for increased nighttime flushing. The following figure was used to determine how the air temperature and concrete thermal mass temperature behaved in July for this single-sided ventilation approach.

![Single Sided Ventilation](image)

**Figure 3c-2.** Air and thermal mass temperature for a single-sided ventilated room.

Dean
The next analysis was used to determine how a cross-ventilated room would compare to a single-sided ventilated room for the same month of July. For the cross ventilation case, we assumed that there was one 4 square foot window at each side of the building, with the configuration of one bedroom on each side of the building with a corridor in between. For the calculations, we accounted for the resistance of the hallway by taking 1/2 of the typical airflow due to wind through a window. This scenario is the same case as the single sided ventilation case. In the next figure, the cross-ventilated room is able to keep the internal temperature lower, by having larger air change rates.

Figure 3c-3. Single-sided ventilation and cross ventilation versus outdoor conditions.
In May of 2000, more analysis was created to determine the benefits for redesigning the building to allow for cross ventilation, instead of the pressurized building and single-sided ventilation approach that had been designed for the new dormitory. In the following figure, both air and concrete thermal mass temperatures are shown for single-sided ventilation and cross ventilation.

The room modeled is the same bedroom from the previous analysis. The room heat gain is modeled as having 400 watts of room loads with the total room loads increasing to 600 watts due to daytime solar heat gain. The airflow through the room is on throughout the times of the day when the indoor temperature is higher than the outdoor temperature. Therefore during the day, the airflow is purely minimum airflow, so that it does not get heat gain from the outdoor air. It was determined that the cross ventilation approach would be the desired natural ventilation approach, as it maintain lower room temperatures throughout the hot season. It was also noticed that the thermal mass can have a beneficial effect on the room temperatures.

![Graph showing outside temperature vs. indoor temperature, cross ventilation vs. single-sided ventilation over a 3-day period.

The graph shows the outdoor temperature in °F and indoor temperature in °F, with data points for each day from July 19 to July 22.

Figure 3c-4. Single-sided ventilation versus cross ventilation over a 3 day period.
At this point in the analysis, it was evident that we would need simple output graphs to make the points of the analysis easy to understand. The following figure was used to show the group discussing the design of the dormitory how significant the benefit for increased airflow rate is. In this chart, it can be seen that there are less hours using cross ventilation above 75 degrees Fahrenheit.

**Indoor Temperatures**  
*Single Sided vs. Cross Ventilation*  
400 - 600 Watts (with Solar)  
50 cfm at 55 °F & Windows Operable

![Chart showing Indoor Temperatures](chart.png)

**Figure 3c-5.** Number of hours within specified temperature ranges.
By June 2000, more analysis was needed to try to convince the design engineers that more design approaches should be considered before settling with the “Puff” and single-sided approach that was designed by this point. The “Puff” approach, as we understand the design is to condition air at the roof top and distribute the conditioned air through a series of ducts into the bedrooms, with no return air. This design would pressurize the building moving air out of the building rather than recirculating air, which will help the indoor air quality, but will also push the conditioned air out of the building. In our analysis we modeled the Puff system as an airflow rate of 50 CFM and an air supply temperature of 55 degrees Fahrenheit, as it was described to us. Figure 3c-6 was used to determine how the “Puff” conditioning compared to the conventional air conditioning. It was found that there could be energy benefits to using the Puff system at low conditioning temperatures, but that the cooling load on the chiller plant would be lower when using the traditional air conditioning system. The airflow rates shown at each temperature are the rates of the flow created from a mechanical fan to assist the natural airflow when the windows are open.

![Energy Loads for AC Types](image)

**Figure 3c-6.** Puff vs. AC - energy and peak cooling load at various cooling set points and airflow rates.

It was further discovered that the “Puff” system did not even guarantee comfort for the occupants, as it often conditioned air that would then get pushed out of the occupied space rather than circulating any air for energy saving and increased thermal comfort.
In figure 3c-7, it was noticed that in all cases that both the peak indoor temperature and the cooling degree days (CDD) were higher for the “Puff” case. Cooling degree days were helpful in understanding how comfortable occupants will be in the space, as the sum of the cooling degree days is a summation of the times when people would be uncomfortable from a thermal standpoint. In this case, cooling degree days is the degrees Fahrenheit over the comfort point multiplied by the length of time that the temperature is over the comfort point. It is also important to notice that the conventional air conditioning peak temperature is equal to the temperature set point, since it removes all of the heat gain during any given hour to maintain thermal comfort. The “Puff” system does not guarantee this same comfort, since it has a maximum airflow and a minimum supply air temperature.

![Comfort Study for AC Types](image)

**Figure 3c-7.** Thermal Comfort of AC vs Puff

**Natural Ventilation Analysis Tool Conclusion**

After months of analysis and development of a tool to analyze how natural ventilation can affect the design of the new dormitory at MIT, we found that even our simple analysis gave insight into what systems should be considered. It was then determined to further develop the tool into an accurate, simple and accessible tool for designers to use. In the following section, there is further detail on how the tool was created and transformed into a more accessible tool.
Chapter 4 The Analysis Tool

![Building Information Table]

**Figure 4-1.** NV Alpha Tool Building Information Input Screen

The Need: Why did we need to put together an analysis tool?

The Natural Ventilation Design Advisor was created to give insight to the possible advantages of using natural ventilation techniques for buildings in the United States. The first step in creating this tool happened as we tried to understand the design of the new MIT undergraduate dormitory architecturally designed by Stephen Holl. The Building Technology Program was involved in the review of the design, as there was a desire on the part of MIT to create an energy efficient building.

To understand and predict the performance of the new residential building, the Building Technology Program worked with a consulting engineering firm in an attempt to create a better product. We found that the consulting engineers in the industry were not able to take the time to break down the issues and understand how the building will truly perform. It has been common to look at airflow studies of buildings with a steady prevailing wind, or to look at the energy performance of a building with mechanical ventilation, and also to look at air chamber studies to help determine the best design of a building. We needed to simplify the process and find accurate predictions for natural ventilation, so that we could have the opportunity to enhance the effectiveness of the design for the new dormitory.

This analysis tool started as a simple and accurate estimation and comparison tool to understand how different natural ventilation approaches could create better comfort and save energy for the residents of the building. After researching the effects of different design issues, the tool brought equations together to understand natural and mechanical ventilation, cooling loads, and comfort indexes, to give a quick feel for how a building design could be enhanced.
Simplification of the strategy and analysis

CALCULATIONS
With the goal to create a simple tool, only the most influential building energy loads were to be calculated with precision, while the less important building energy loads could be estimated to get reasonable accuracy with the simple tool. The series of calculations that we calculate to create the analysis include the following:
1. Airflow between exterior and interior of the building
2. Bulk indoor room temperature
3. Average thermal mass temperature
4. Average indoor humidity
5. Internal room loads
   a. Mechanical and lighting loads
   b. Human latent and sensible loads
   c. Solar loads

INPUT
The inputs include the following major categories:
1. Weather data
   a. Outdoor dry bulb temperature (°F converted into °K)
   b. Wind speed (knots converted into m/s)
   c. Hour (used to determine day and time of day)
   d. Direct normal solar (BTU/hr*ft² converted into Watt/m²)
   e. Outside humidity (g/g used as percentage)
2. Building information
   a. Room dimensions
   b. Window & glass dimension, location and characteristics
   c. Number of operable windows
3. Systems information
   a. Cooling COP (Coefficient of performance)
   b. Fan flow rates
   c. Ventilation type (SSV, CV, stack, none)
   d. Window operation (open, closed, optimized, night cooling)

OUTPUT
With the use of these inputs and the calculation used for the analysis, we find the following output data:
1. AC energy (kWh) (sensible, latent, total)
2. AC peak load (kW) (sensible, latent, total)
3. Window fan energy
4. Indoor peak temperature
5. CDH (cooling degree hours) (°C x hours)
6. Number of hours out of comfort zone
Methodology: Simple Heat Transfer Approach

The initial heat transfer approach looked to model the most influential conditions for a building concerning how natural ventilation moves into and through the room. The simplifications include the following:

1. One Room Analysis – assuming that we would get a feel for the entire building by modeling a room that would have the worst conditions for natural ventilation.
2. Bulk Room Temperature – assuming little deviation in temperature throughout the room.
3. Simple Solar Approach – assuming percentage of the solar available at each hour, later changed into modeling sun path to determine percentage.
4. Simple Room Loads – created estimates of how energy loads would be created in the rooms, such as from people, lighting and computers.

Figure 4-3 is an illustration of how the initial simple heat transfer model was being modeled in the excel version of the analysis tool.

Figure 4-2. Simple Heat Transfer Model used for Alpha Version
Methodology: Addition of Solar Angle Calculations

Due to the influence of solar gains on the buildings heat transfer behavior, it was determined that the solar loads would have to be calculated with greater accuracy. This was accomplished through modeling the sun path throughout each hour of the year to determine how much sun is available of the external walls and windows. The calculations used to determine the available solar are in Appendix C.

Methodology: Addition of Humidity Calculations

Humidity calculations were refined to be more accurate since it was determined that the latent and sensible energy calculations were needed for comparison of regions that had higher outside humidity. In addition to the energy concerns of removing the humidity, the refined humidity calculations allowed for additional humidity and comfort based decisions for using natural ventilation. The calculations used to track the humidity in the building are in Appendix C.

Comfort and Energy Output

The output portion of our analysis is very important in trying to understand the possibilities for having natural ventilation in buildings. In the following figure there are three columns of output data, AC Air ("Puff"), AC Coil (conventional air conditioning), and No AC (natural ventilation with fan assist possible), which were used to determine how the building performed.

<table>
<thead>
<tr>
<th>Energy Simulation Results</th>
<th>sensible</th>
<th>total</th>
<th>sensible</th>
<th>total</th>
<th>No AC Energy</th>
<th>N/A</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Air Energy (kWh)</td>
<td>367.5</td>
<td>425.6</td>
<td>219.3</td>
<td>313.3</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>AC Air Comfort</td>
<td>97.7%</td>
<td></td>
<td>95%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AC Air Peak Load (kWh)</td>
<td>2.615</td>
<td>2.651</td>
<td>0.631</td>
<td>0.675</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AC Air Fan Energy (kWh)</td>
<td>N/A</td>
<td></td>
<td>29.0</td>
<td></td>
<td>63.6</td>
<td></td>
</tr>
<tr>
<td>AC Air Peak Temp</td>
<td>91.5</td>
<td></td>
<td>80.0</td>
<td></td>
<td>95.5</td>
<td></td>
</tr>
<tr>
<td>AC Air CDH</td>
<td>388.9</td>
<td></td>
<td>0.0</td>
<td></td>
<td>1080.4</td>
<td></td>
</tr>
<tr>
<td>AC Air Temp (°F)</td>
<td>203.0</td>
<td></td>
<td>458.0</td>
<td></td>
<td>447.0</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4-3. NV Alpha Tool Energy Simulation Results Screen

In the rows of information in the three columns, the various results are shown for both comfort and energy concerns. In terms of energy, both energy usage and peak energy load were calculated to determine the size of the system and the cost for operating the system for the year. In terms of comfort, we calculated various comfort conditions to get a better understanding of how the building performs. The first is the percentage of the hours that are comfortable; we found that this was less useful, as it did not tell us how uncomfortable the hours were. Next we calculated the peak temperature to get a better understanding of how uncomfortable the room was.
This data was useful in creating an understanding of the room’s comfort, but we found it most useful to use the last two comfort results. "CDH" is the cooling degree hours for the room, which tells us the sum of all of the hours where the temperature is over a comfortable temperature multiplied by the number of degrees over the comfortable temperature during each of those hours. The last comfort calculation that we used is the number of hours that the temperature is over the cooling set point. In addition to these comfort conditions, a future upgrade in understanding the comfort of the building throughout the year is to plot a psychometric diagram, which plots the temperature and humidity together to understand true comfort of the occupants.

Verification

Throughout the process of developing the natural ventilation design tool, the output data was analyzed for verification purposes. Each step through the development allowed Professor Glicksman and I to check hourly airflow, energy and air & mass temperatures calculations.

Beyond the standard verification, we looked at how the tool was modeling the resistances of the fans through the window opening into the room. If the pressure drop from the resistance was higher than the fan was capable of blowing, then the airflow would be modeled incorrectly. We looked at a 10" fan volume flow to determine if the pressure drop was low enough. The following calculation shows that the pressure drop of .17 Pascal across a four square foot window was small compared to the pressure drop that the fan creates, meaning that the airflow was being accurately modeled.

\[
\text{Window Area} = 4 \text{ ft}^2 = 0.372 \text{ m}^2 \\
\text{Volume airflow by 10" Fan} = 0.26 \text{ m}^3/s \\
\text{Change in Pressure} = \Delta P = \frac{1}{2} C_d \rho V^2 = (0.5)(0.6)(1.177)(0.26/0.372)^2 \\
\Delta P = 0.17 \text{ Pa}
\]

In a larger effort ensure the accuracy of the equations and results of the alpha version of the tool, I worked with Henry Spindler, another student in the Building Technology program at MIT. Mr. Spindler previously created an energy analysis program that is able to model steady airflow situations created by mechanical ventilation in commercial buildings. The first step in comparing our programs was to set a standard building case that could be modeled on each program. The following building setup was used for our modeling scenarios:
The first general comparison that we made was for the comfort hours and cooling degree hours achieved in the occupied space. In the first set of runs, we found that we did not have comparable numbers. The alpha tool determined 7550 comfort hours and 4500 cooling degree hours, where the energy tool determined 7900 comfort hours and 2250 cooling degree hours. From these numbers we found that there was a difference in the way that we modeled both the solar loads and the thermal mass.

A closer look at the thermal mass found that the alpha tool was using 170 cubic feet of thermal mass and the energy tool was using 1500 cubic feet. With adjustment to the thermal mass on the energy tool, the energy loads went up as much as 5 times on the hot days of the summer, bring the total energy over the year closer. The two tools still had enough difference that we needed to take additional steps to find which calculations we modeling the same and which were different.

After the adjustments to the thermal mass volume, we were able to look into the other differences in energy consumption, which we needed to further breakdown. The method used was taking out individual loads at a time to see if the percentage of energy increase or decrease is comparable. Through this process, it was found that the overall energy calculations were small percentages apart when the solar and humidity calculations were taken out. This led to the creation of more in depth calculations on both the solar and humidity loads for the alpha tool, which were modeled more generically before. The solar and humidity equations, which are based on equations and methodologies in the energy tool, can be found in Appendix C.
Getting the tool written into Java

The methodologies used in the alpha version of the natural ventilation tool have been translated into Java. The Java code will be used to make the tool accessible from the web. A large part of converting this tool into Java was getting a complete understanding of the methodology so that others who may work on the code in the future could understand each part of the analysis. The following are flow charts that were used to convey the methodology of the tool. Please note that the terms can be found in Appendix D.

**Figure 4-5.** Night time cooling decision methodology

**Figure 4-6.** Latent energy methodology
Figure 4-7. Single sided ventilation airflow methodology

Figure 4-8. Cross ventilation airflow methodology
Figure 4-9. Optimized window methodology based on Thermal Comfort

Figure 4-10. Optimized window methodology based on humidity and temperature

Figure 4-11. Energy balance for the room based on an optimized window. (energy in wattage from room loads, airflow, thermal mass and air conditioning)
Figure 4-12. Data flow between sections of the java code for the alpha tool conversion.

Figure 4-13. Decision tree for how the temperatures react to different loads.
Joining into MIT Design Advisor

The MIT Design Advisor, originally developed as a tool for understanding how double-skin facades can enhance the performance of a building, will be further developed with the addition of the methodologies and calculation of the natural ventilation analysis tool. The first step in joining into the MIT Design Advisor is to get a simple version of the natural ventilation tool online, so that verification can occur. After the tool can analyze natural airflow online, enhancements can be made to the input and output capability, to increase capabilities where needed.
Chapter 5 Implications of Energy Analysis

Natural Ventilation can be used in many buildings throughout the United States. Energy analysis using the natural ventilation design advisor gives insight into where and how natural ventilation can be used in a building's design.

Early in the process of understanding where natural ventilation could likely be used, we looked at weather data, including psychometric diagrams, heating and cooling degree day maps, and humidity or precipitation maps. The following figures helped to give us an initial understanding of the climate in the United States.

Figure 5-1. Heating and Cooling Degree Day map for the United States

The heating and cooling degree-day data indicates which areas are likely to have time when ventilation can be used for cooling a building.
Figure 5-2. Average Annual Precipitation map for the United States

The average annual precipitation, does not give a direct indication as to the amount of humidity in the areas throughout the country, but does give a general sense to which parts of the country are likely to have higher or lower humidity.

After looking at the weather data for the United States as a whole, we looked a data for cities within certain typologies, including mild cities, hot and humid cities and hot and dry cities. From the maps above we chose the following cities to look at each of the categories:

<table>
<thead>
<tr>
<th>Mild Cities:</th>
<th>New York City, NY</th>
<th>Chicago, IL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot and Humid Cities:</td>
<td>Atlanta, GA</td>
<td>Kansas City MO</td>
</tr>
<tr>
<td>Hot and Dry Cities:</td>
<td>Phoenix, AZ</td>
<td>Los Angeles, CA</td>
</tr>
</tbody>
</table>

The first step to get a better understanding of any results from analyzing these cities is to understand the weather data and the local climate. The following psychometric charts were used to understand how the weather data may effect the natural ventilation analysis.
MILD CITIES:

New York City, NY
Comfort Chart

- Jan 1 - Mar 15
- Mar 16 - Jun 15
- Jun 16 - Oct 15
- Oct 16 - Dec 31

Temperature (°C)

Humidity (water air)

Comfortable with 2 m/s airflow

Cooling Season Comfort Zone

Figure 5-3. Psychometric Chart for New York City based on TMY2 data.

Chicago, IL
Comfort Chart

- Jan 1 - Mar 15
- Mar 16 - Jun 15
- Jun 16 - Oct 15
- Oct 16 - Dec 31

Temperature (°C)

Humidity (water air)

Comfortable with 2 m/s airflow

Cooling Season Comfort Zone

Figure 5-4. Psychometric Chart for Chicago based on TMY2 data.
HOT & HUMID CITIES:

Atlanta, GA
Comfort Chart

Figure 5-5. Psychometric Chart for Atlanta based on TMY2 data.

Kansas City, MO
Comfort Chart

Figure 5-6. Psychometric Chart for Kansas City based on TMY2 data.
HOT & DRY CITIES:

Phoenix, AZ
Comfort Chart

Figure 5-7. Psychometric Chart for Phoenix based on TMY2 data.

Los Angeles, CA
Comfort Chart

Figure 5-8. Psychometric Chart for Los Angeles based on TMY2 data.
Mild Cities:
The New York City and Chicago weather data proved to be comparable when looking at the psychometric diagrams. Chicago had slightly more hot and humid hours than New York City. It was noticed for both of the mild cities that almost every hour of the year’s outdoor weather is either below or within the comfort zone when you add 2 meters per second of airflow. The Chicago weather data will be used for the in depth analysis to determine the feasibility of natural ventilation in mild cities in the United States.

Hot and Humid Cities:
The Atlanta and Kansas City data were both hotter and more humid than the mild cities, and were reasonably similar. Kansas City has more hot and humid hours than Atlanta, and will be used for more in depth analysis to determine the feasibility of natural ventilation in the hot and humid cities in the United States.

Hot and Dry Cities:
The Los Angeles and Phoenix weather data showed that these cities are dryer than the other cities. However, the Los Angeles weather data did not prove to be acceptable for our analysis of a hot and dry city, due to the lack of high temperatures in the weather data. Phoenix, which looks more accurate, will be used for more in depth analysis to determine the feasibility of natural ventilation in the hot and dry cities in the United States.

Building analysis for determining feasibility of using natural ventilation in the US.
The following building characteristics were used as the base case for analysis of the cooling energy usage for the three cities:

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling Set Point</td>
<td>80 degrees Fahrenheit</td>
</tr>
<tr>
<td>Heating Set Point</td>
<td>68 degrees Fahrenheit</td>
</tr>
<tr>
<td>Nighttime Cooling Set Back</td>
<td>60 degrees Fahrenheit</td>
</tr>
<tr>
<td>Mechanical Fan Assist</td>
<td>0 CFM</td>
</tr>
<tr>
<td>Thermal Mass</td>
<td>Concrete floor and ceiling</td>
</tr>
<tr>
<td>Room Volume</td>
<td>1500 cubic feet</td>
</tr>
<tr>
<td>Operable Window Area</td>
<td>8 square feet</td>
</tr>
<tr>
<td>Number of Windows</td>
<td>2 (placed on top of each other)</td>
</tr>
<tr>
<td>Height from bottom of top window to top of bottom window</td>
<td>6 feet</td>
</tr>
<tr>
<td>Total Glass Area</td>
<td>16 square feet</td>
</tr>
<tr>
<td>Room Heat Gain</td>
<td>500 Watts plus Solar</td>
</tr>
<tr>
<td>Solar Heat Gain Coefficient (SHGC)</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Figure 5-9. Base case building characteristics used for details analysis.
<table>
<thead>
<tr>
<th>Case</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Case</td>
<td>As Described in Figure 5-9</td>
</tr>
<tr>
<td>Case A</td>
<td>Base Case @ 70 CFM of fan assist</td>
</tr>
<tr>
<td>Case B</td>
<td>Base Case @ 235 CFM of fan assist</td>
</tr>
<tr>
<td>Case C</td>
<td>Base Case @ 550 CFM of fan assist</td>
</tr>
<tr>
<td>Case D</td>
<td>Base Case @ 300 Watts plus Solar</td>
</tr>
<tr>
<td>Case E</td>
<td>Base Case @ 300 Watts plus Solar &amp; 550 CFM of fan assist</td>
</tr>
<tr>
<td>Case F</td>
<td>Base Case @ 0.2 SHGC for Solar Shading</td>
</tr>
<tr>
<td>Case G</td>
<td>Base Case @ 0.2 SHGC for Solar Shading &amp; 550 CFM of fan assist</td>
</tr>
<tr>
<td>Case H</td>
<td>Base Case with NO nighttime cooling setback</td>
</tr>
<tr>
<td>Case I</td>
<td>Base Case with NO nighttime cooling setback &amp; 550 CFM of fan assist</td>
</tr>
<tr>
<td>Case J</td>
<td>Base Case as a sealed building. (Minimum fresh air only)</td>
</tr>
</tbody>
</table>

**Figure 5-10.** Base case building characteristics used for details analysis.

**Figure 5-11.** Annual energy use for tested scenarios listed in figure 5-10.
Figure 5-11. Comparison of annual energy use for tested scenarios.

It is interesting to notice that the largest savings of any of the tested upgrades is the upgrade from a sealed building to a building with operable windows in each of the three cities. Significant energy savings can also occur for a sealed building with the use of an economizer that utilizes outdoor air temperature when it is cool outside and warm inside. The energy savings will be greater for a building with operable windows due to the lower resistance in moving air through a window compared to moving through a duct system. Of the other upgrades, they generally have comparable percentage savings between the three cities.

Cases A, B, and C test the savings associated with using a mechanical fan to assist the natural airflow through the window. The moderate airflow of the 235 CFM fan offers the largest percentage savings per CFM and energy used by the fan. The mild climate of Chicago sees the greatest benefit from using the mechanical fan assist.

Cases D and E were modeled to test the savings associated with minimizing the heat gain within the occupied space, such as more efficient lighting, computers, and equipment, or by having fewer people work in the space. This upgrade alone has a larger effect than any of the mechanical fan upgrades. It is also interesting to notice that the percentage of savings is fairly uniform for each of the cities.
Cases F and G were modeled to test the savings associated with the upgrade of the solar shading capability of the windows or shading devices near the windows, such as overhangs, blinds or landscaping. This upgrade again was fairly uniform amongst the cities, but Phoenix does get more savings from this than the mechanical fan assistance.

Cases H and I were modeled to test the savings associated with the nighttime cooling temperature setback. Chicago, the mild climate, is the only city that receives significant energy savings from the use of a nighttime temperature setback, due to the higher nighttime temperature in the hotter climates.

Case J was modeled to test the benefit associated with using natural ventilation compared to using a sealed and fully air conditioned building. As stated before, this is where the largest savings occur for each of the climates, due to the high cooling loads associated with sealing all of the heat gain in the building for the air conditioning system to remove from the building.

In addition to this analysis, the beta version of the natural ventilation design advisor will be capable of understanding the hourly internal humidity ratios. Currently in the alpha version, since it is an excel spreadsheet larger than 50 megabytes large, the humidity calculations are in a separate spreadsheet at almost 18 megabytes large. Due to the size of these tools and the number of calculations, the computer was unable to handle calculation them simultaneously as would be advantageous for tracking the internal humidity.

**Conclusion of Implications of Energy Analysis**

The use of simple energy analysis gives major insight into the benefits associated with better building engineering and design. The analysis above allows us to break down individual building design characteristics and determine how they effect the building performance, and in particular the natural ventilation characteristics. A design tool of this analysis capacity can be very helpful for designers throughout the design phase, but in particular at the start of the design, where many design features are easier to change.

It is important to note that the above analysis was created to get a better understanding of the possibility to use natural ventilation in building throughout the United States. The analysis also does not try to optimize the natural ventilation technologies; instead it gives a general look at major technologies that can influence the capability to use natural ventilation. In many cases it would be advantageous for designers to consider using natural ventilation in the lower heat gain zones of the building as the primary cooling system. In certain climates, in addition to the natural ventilation minimizing the air conditioning load, with proper design, natural ventilation can be used as the buildings entire cooling system.
Chapter 6 Conclusions and Recommendations

This thesis is setup to give insight at many levels to the possibilities for using natural ventilation here in the United States. At an introductory level it explains the different forms of natural ventilation to give a basis for further understanding. The next step is through understanding how these concepts are used in buildings that were visited throughout Northern and Western Europe. To both further this understanding and to give information that will lead to future research, we look at some more concepts of natural ventilation design that are used in other buildings that were found through literature search.

After an understanding of natural ventilation is created, this thesis discusses energy analysis using different tools with different capabilities. Due to variation with respect to the capability to model mechanical and natural ventilation for buildings, a need is determined to help understand how naturally ventilated buildings perform. These needs are then transformed into an energy analysis program specifically set up to be simple and accurate and model natural ventilation behavior. Finally we try to understand the impact of using natural ventilation on buildings throughout the United States.

The United States building industry has significant opportunity to use natural ventilation in many forms of building design. Through a better understanding of how the building design details affect the operational costs, including energy, building owners will be the first to recognize the benefit to using operable windows to induce the transfer of hot air out of the facility. This thesis recognizes that in most cases in the United States there is little chance to design a building without the capability of using conventional air conditioning. However, natural ventilation can be used to assist or do complete natural air conditioning, therefore minimizing the size of the equipment needed for each building. Building construction and operation costs can both be lower due to decreased cooling energy use and cooling energy load, that determine the size of the equipment needed for the building.
Appendix A: Buildings that use Natural Ventilation – Building Visited
Summer 2000

The buildings will be listed in this section in the order in which they were visited, starting with buildings in Denmark and then on to Germany, Belgium, the Netherlands, Scotland, and England.
WindowMaster Headquarters, Vedbaek, Denmark

WindowMaster Headquarters, renovated in 1995, is located in Vedbaek Denmark, and is an example of a building retrofitted to be energy efficient. The building helps the company WindowMaster show how their services and technologies can help to both save energy and increase comfort of a working environment. The entrance to the building is exterior to the original building, therefore creating a zone between the interior and exterior of the building as a moderate climate. This zone is also utilized as a greenhouse, atrium, and stairwell, which can then be used to move air up and out if too hot or gain solar energy if too cold.

While visiting this building, we meet with WindowMaster to share knowledge and research on natural ventilation products and other building technologies. While conducting our meeting, we were able to witness the use of the windows, shown below. Throughout our meeting, the top windows were open giving us a steady airflow. As a demonstration, we also saw the large windows open allowing more airflow, which was unnecessary, as the day was moderately cool.

The building also dealt with fire codes while trying to maintain as open an air space as possible. A long corridor allows cross ventilation from each end of the length of the building, while there are a series of fire doors that allow the building to have increased airflow and pass the fire code inspection. Additionally, through the mid section of the building widthwise, there is a very open floor plan to allow airflow across the long corridor. Additional airflow is created through stacks that go up to operable skylights in the corridors.

Pictures A-1,2,3: (1) Long hallway with fire doors. (2) Operable windows in conference room. (3) Skylight in hallway.
Aston’s Administrative Building, Copenhagen, Denmark

The building for Aston, near the waterfront of Copenhagen, includes a combination of naturally ventilated and mechanically ventilated spaces. Most of the space is naturally ventilated through the combination of operable windows, building management system, open floor plan and an atrium through the length of the building. The spaces that are mechanically ventilated include the "canteen" (entry atrium space), the meeting rooms, the kitchens and bathrooms. These spaces we determined to need mechanical ventilation for code, or comfort issues with public usage.

The natural ventilation works in either low or high wind situations because of design features. In low wind situations, the use of the stack effect occurs when the atrium skylight window open, allowing hot air to rise up and out of the building. In higher wind situations, cross ventilation occurs when the office space windows are open, allowing the wind to come in on one side of the building and out the other. The control system communicates with the heating system to determine when to switch to winter strategy, which includes turning on the hot water for under the window sill room heating or allowing windows to open. This helps the user through advising toward a conditioning strategy.

The details of each naturally ventilated building can help to understand the overall strategy. In the Aston building, window controls are every 3 meters throughout the office space, to allow for increased control by the users. In addition, the blinds are placed between two panes of glass, within the window unit, and are controlled by a motor and the control system, allowing for user control and minimal weather abuse of the blinds.

Pictures A-4,5: (4) Outer wall with a lot of glass. (5) Glass ceiling over atrium with operable skylights.
Danish Magister Union Building, Copenhagen, Denmark

The Danish Magister Union building, which is located in a renovated old manufacturing building, uses the existing building to allow the new offices to use the existing tall ceilings, to create more open spaces for air movement. The height of the ceiling was particularly noticeable in the hallway, which ran through the center of the length of the building. One interesting abnormal design feature in the hallway is the use of oversized fire doors, such that when they are open, you do not notice that you are walking through a doorway, but rather just like a hallway.

The building also has an open area for an eating space and an open stairwell, which allows for airflow across the width of the building. The open stairwell is allowed here, as the enclosed fire stairwells are located at each end of the rectangular shaped building. Additional airflow across the building can occur through the offices spaces, which have operable windows both to the exterior and also into the hallway.

Both the windows into the hallway and the large window that open to the exterior are manual, but both the external shades and the smaller windows at the top of the wall to the exterior are mechanically operated. The external shades, as seen in the 2nd picture, are semi-transparent to allow some vision to the outside, while blocking a significant amount of sun from entering the building. The building is setup such that the office spaces start on the second floor, as they have unrenovated storage space on the ground floor.

Pictures A-6,7,8: (6) External wall with operable windows. (7) Operable window and external blind. (8) Internal operable window between office and hallway.
Roskilde University, Roskilde, Denmark

With a tour of a building at Roskilde University, it was evident when we entered the building that the system was not working properly. The weather for the day was nice, while the comfort and air quality were noticeably worse than the other buildings that we visited on the same day.

The system in this building was a combination of natural and mechanical ventilation, as the classrooms and some of the offices were mechanically ventilated, while for the offices facing into courtyard and the public spaces were naturally ventilated. There is no direct ventilation into many spaces, including the large atrium spaces, as many spaces depended on fans to pull air around the ceiling and outside. This did not seem to be overly effective for those that were working on a non-typical schedule. During these times, the airflow could not occur from the office spaces to the hallway and then to the stairwells, as the doors would be shut for security or because of lack of knowledge of how the air moves through the doorway. Additionally, since the doors close every night for security, it is not possible to use natural night ventilation as a strategy of cooling the building during the hot seasons.

Mechanically operated blinds are located inside the windows throughout the building, which keeps the sun from entering the building, but allows solar heat gain on the windows. The stairwells create a small atrium next to the hallway, allows heat to come from the building spaces and out through the skylight above the stairwell. On the outside there is an overhang at the highest level in the courtyard side of the building, which looked nice, but did not shade everything, but may ease some of the top floor heat gain concerns that we found in many buildings.

Pictures A-9,10: (9) Overhang, windows and window blinds. (10) Volume between drop ceilings for air movement via mechanical ventilation.
Sofiendal School, Sofiendal, Denmark

The Sofiendal School, outside of Copenhagen is a new naturally ventilated building amongst older portions of the school. The new building takes the same basic structure of the classic one story school, but gives the classrooms tall ceilings that get taller toward the center of the building, as the roof goes up to a pitch. Near this pitch, airflow is allowed to leave the room through a ceiling vent.

To induce ventilation through the room, mechanically operated windows are located on the exterior wall of each classroom. Night ventilation is also allowed, since the opening size is controlled by the "BMS" (building management system), which allows for increased security and controlled airflow. The cooling strategy allows for natural ventilation to work for temperatures below 24 Celsius, while using it as night ventilation down to 19 Celsius. The use of fan only occurs in the late hours of the night if needed.

The strategy works well, as the students are healthy and the teachers often prepare their lectures in the new building, even if they teach in the older sections of the school. Additional features that help with the natural ventilation include the external shading on the courtyard side of the building, which helps to keep some of the direct and reflected solar gains out of the building and off of the walls. Also, each classroom has a door that can be held open if extra airflow is needed. Inside the buildings, the tall cathedral ceiling hallways help to feel more spacious as well as to create a large space for the temperature gradient to spread out, with the highest temperatures near the roof.

Pictures A-11,12: (11) Tall ceiling, vent opening at the corner of the ceiling and vertical opening between rooms. (12) External shading overhang and operable windows.
Commerzbank headquarters, the tallest building in Europe at 60 stories, uses natural ventilation to supplement its cooling strategy. Through the use of 3,000 motorized office windows, 100 larger atrium garden windows, 10 weather stations, and large amounts of area set aside for atrium airflow, this tower is able to minimize the cooling load, such that it uses less electricity than was originally designed for.

Upon entering the triangular shaped building, we walk through an automatic revolving door into a large lobby and atrium space. The 30,000 cubic meter lobby, at 1/3 of the floor area of the footprint of the building and 2 stories tall, felt even larger with the additional 2 stories in the center atrium and the adjoining glass walled café. The lobby performed as its own system, with large exhaust fans at the ceiling taking the heated air from the space. Additionally these fans can be used to ensure that good indoor air quality is maintained, due to the fact that smoking is still permitted here.

The café, next to the lobby area, has stacks of three windows lining the exterior wall near the ceiling of the space. The large windows look to be approximately 1 meter tall by 3 meter wide. All windows were open in the morning, before the café was open. While they were all closed when we were leaving the building when the café was open. We were informed that the caterer has operation of the controls for their space. It looks like they have a strategy to cool the space naturally through the morning cooking, but close the windows to prevent unwanted drafts on the café patrons.

The office spaces of this building, as many others in Europe are designed for the health of the user. Firstly, every user has daylight in their office, such that the height of the window would be larger if the depth of the room increased to more than 6 meters deep. The offices are also set up for the user in terms of climate control, as each user can increase of decrease the amount of outside air comes into the office. All offices also have sprinkler and fire detectors as well to increase the safety of the building.

Even as the office spaces use outside air, they still use both heating and cooling in the spaces throughout the year. As the offices need heating, steam is used under the windowsills to heat up the space. As the offices need cooling, there are three strategies that can be used, first is natural ventilation with the opening of windows, while second is mechanical ventilation, and last is the use of air conditioning through the chilled ceiling, using steam absorption chillers. The building manager believes it would be impossible to operate this building without the use of air conditioning. In the second picture, you can see the openings for the air conditioning and mechanical ventilation on either side of the light fixture, by noticing the dust marks.

The office windows, as show in various pictures, are 1.5 meters wide and 2.15 meters tall, with double glazed windows at the exterior of the office space, and then an additional single glazed window as the outer skin of the double skin facade system. The windows open into the office, away from the 200 mm. gap between the two skins of the facade. The window can either tilt in from the top, or open like a door to create maximum air movement.
The garden atrium spaces can be seen from each interior facing office space, as a source of fresh externally conditioned air and daylight. The object of the atrium spaces throughout the building is to create an indoor climate, similar to the outdoor climate, with the exclusion of precipitation. Natural ventilation is used throughout the year in these spaces, except for two extreme conditions, over 25 Celsius and below 3 Celsius, where the mechanical ventilation is used to moderate the atriums climate.

The natural ventilation occurs in the atrium spaces through large single skin facade windows at the top of each atrium exterior. These windows, as seen in the first picture on the second page of pictures, are larger and heavier than the office windows. Additionally, because these windows are in direct contact with the external climate, with no protection of an additional skin, they have had mechanical failures in these windows more often. With this orientation to the exterior, large amounts of air transfer can occur into the space, so that the offices adjoining the garden atrium can receive the natural condition that they need. Depending on the wind and weather conditions, the large garden windows typically open and close anywhere from 10 to 20 times per day.


Picture A-16: Operable external windows, fixed skylights and operable fabric blinds.
Pictures A-17,18: (17) Air opening in the double-skin façade. (18) Office window opening like a door with operable blinds between window and external glass.

Pictures A-19,20: (19) Large operable windows in atrium gardens. (20) View from atrium garden into atrium cavity and offices.
Main Tower, Frankfurt, Germany

The Main Tower in Frankfurt is an example of how a building can function with mixed use or multiple types of tenants. Unlike Commerzbank, just down the road from Main Tower, this building has dozens of tenants, who are not focused on the long-term effects of the use of their space. While the tenants have the capability of using natural ventilation in their spaces, it is not seen as a whole building cooling strategy.

As you enter the building, you enter through a revolving door into a single story lobby that stretches over most of the building. The lobby increases in height through the stairwell into the second and third floors. This height difference could be used to move the hot air up to the top of the lobby space, but was not. The external windows were not open even though we heard significant noise in the lobby from fans pulling out the hot air on a moderately cool day. At one end of the lobby, away from the reception desk, an audio-visual media art exhibit was covering much of the ceiling fan noise.

Upon entering a conference room in the office space of the building, we were able to experience how the external windows open straight out from the building. Also we found that the cool ceiling approach was used to cool off the space when natural ventilation did not keep the space below the set points.

Pictures A-21,22,23: (21) External view. (22) Operable push-out window in conference room. (23) Lobby with stairwell that could be used to pull out hot air.
Victoria Insurance, Dusseldorf, Germany

Victoria Insurance, decided to create their new complex right next to its existing headquarters, and to do it as an energy efficient tower. With a commanding view of the Rhine and a loosening of codes which allowed larger buildings to be built, in July of 1998, Victoria Insurance became one of the largest building in Dusseldorf, at 28 stories, and was to be a statement of who Victoria Insurance is. The building would have been even taller, except that it was regulated at the time by a flight path that no longer exists.

The building was to be energy efficient, but more importantly increase the comfort and convenience of the workers. Every room in the complex is regulated, although only the conference rooms, cafeteria and data processing rooms have typical air conditioning, where the other rooms have a combination of natural ventilation and cool ceilings for conditioning in the summer. The low-rise uses a double skin façade to help manage the sounds of the city more than the elements of the climate, as is done in the high-rise.

Details of this improved environment included roof gardens, atrium gardens, artwork, and user controls. The design of the Victoria Insurance buildings created a complex that met a "sensationallly low primary energy code of 286 KWK" per meter squared per year. Over the past couple of years, energy usage in the tower was even lower, at a rate of 170 KWK per meter squared per year. This has resulted in dramatically lower costs to condition this space, at a rate of approximately 70 cents per meter squared per month, as opposed to a more typical cost of about 15 dollars per meter squared per month for traditional air conditioning. The building manager assesses that there is a four-year payback on the installations.

The building has set points, controlled by the system, of 21 Celsius in the winter and 25-26 Celsius in the summer time, while the users of the rooms have additional control to adjust their climate by a couple of degrees. The building also is able to use a cogeneration energy conversion process, which takes the extra heat from the computing and gas to make the some of the cooling, heating, and electricity. Movable upward lighting as well as the light color of the room, requires less cooling to compensate for the heat generated from large amounts of lighting.

Pictures A-24,25: (24) Intersection of low-rise and tower. (25) View into greenhouse that was created for a better work environment.


RWE, Essen, Germany

The RWE tower, the first of the "ecological high-rise buildings" is a great building to look at the concepts that were developed. With the use of a double skin facade to bring in natural air to supplement the air conditioning and mechanical ventilation, the building took a step in an ecological manner from previous buildings of its type. Upon entering the building, you come into a 2-story lobby, with single skin facade and internal metal blinds, both of which allow more heat or cold to enter into the lobby space than could have been designed for. To compensate for this they designed for perimeter heating at the base of the glass and cooling from the holes that run vertically pointing at the glass.

There are no operable windows in the lobby space, which allows for increased security. The lobby does have a large amount of thermal mass, with the majority of the construction being concrete and granite, and was cool to touch at 9:45 AM. We found that the air is conditioned throughout the year into the lobby space, so that people enter into a comfortable space. There is question as to the performance of this space with regards to conditioning large amounts of thermal mass throughout the year.

After our visit in the lobby, we were brought to the conference room at the top floor of the building. This space has glass around the perimeter that does not allow air to pass from the room to the perimeter hallway. This space is also conditioned throughout the year, with air intakes through the carpet in the center of the room. The room is conditioned through a cool ceiling in addition to conditioned ventilated air. A nice design feature in the conference room is the ceiling shading device for a circular skylight.

The typical office allows for a large amount of floor space per person, since the majority of the employees in this building are the executives of the company, which keeps the cooling loads per floor area low. Each room has manually operable windows that open into the double skin facade space, allowing naturally ventilated air to enter the office. All of the windows are closed for the night, as they do not do nighttime cooling to alleviate extra cooling loads. Each office can also be adjusted by 3 Celsius for the room temperature.

Pictures A-33,34: (33) Glass perimeter wall in conference room. (34) Air intake carpet.

Pictures A-37,38,39: (37) Weather station at the roof top. (38) Single-pane façade at lobby with small circular conditioned air outlets pointing at the glass. (39) External view.
Stadttor, Dusseldorf, Germany

A very large atrium runs through the center of the Stadttor, and a deep double skin façade wraps around the building to create transparent ends of the building. The design allows for both cross and stack ventilation through the atrium, and cross and single-sided ventilation from the office space into the atrium. In the atrium lobby, orange rubber flooring was used, which creates two inconsistencies with typical natural ventilation design. First is the insulating property, creating less thermal mass to help regulate the temperature. Second is the large amount of pollutants that are emitting into the fresh air supply for the users of the building, both from the rubber and the installation glues. An additional inconsistency occurs with the fresh air supply of the building being located directly next to the parking and the direction of the movement of the cars on the highway.

Other than these inconsistencies, many good design features were created for this building. The design process was delayed by 2 years because of regulation hurdles, but this delay ended up helping them to redesign the building features for better airflow and increased energy efficiency. We were told that the redesign made it possible to get 300-400% increased airflow rate through the façade. This design process also brought the design through a few different design firms including Ove Arup, HL Technique, and then finally DS Plan which they were most confident with the results.

In an attempt to understand the performance of this building, the property management group has been performing a ½ year of data collection. It was noted though that they have had two very mild years in Dusseldorf, which may be deceiving about the functionality of the building. Overall though they feel that the building is performing well, and would also perform well on more extreme years. Currently they have been using the natural ventilation for 70% of the year. The use of the natural ventilation comes from two distinct design features of the building. First is the atrium space, which allows air into the building throughout the year until the outside temperature gets below 5 Celsius. Second, air can enter through the outer skin of the double skin façade, which would then enter the perimeter office spaces when the operable windows were opened.

The building uses the concept of heating and cooling by transport of water, while using air transport to remove impure air and humidity. It was noted that the cooling strategy is "cold head and warm feet". The building uses ground water for cooling in copper tubes in the cool ceiling. The building also uses a salt wheel to dry and cooling incoming air for the ventilation system. The ventilation system is zoned per floor, with on, off, or auto, while the water is zoned per office, where the user is able to adjust the temperature by +/- 3 Celsius. The property manager noted that there is a study showing that people are not able to tell the difference with 1.5 Celsius change in temperature.

The building uses two weather stations on the roof, 32 weather stations around the perimeter of the building at 8 different levels and 4 different locations per level, as well as sensors in the atrium space. The weather stations are used for wind direction and speed, rain, sun, and temperature. The controls, operated by the building management system also control the blinds for the office spaces to keep the sun away from the conditioned spaces even when the users are not in their offices. These blinds are much
quieter than others that we had seen in previous buildings on our trip. Additionally these blinds do not allow any daylight through, unlike other buildings, which keep the blinds more transparent. The blinds have been a concern for the users of the building, as they often do not understand why the blinds are moving.

Pictures A-40,41,42: (40) External view showing atrium and highway. (41) External view showing operable window at the top and bottom of atrium. (42) View from lobby showing rubber flooring, parked cars and highway.

Pictures A-43,44,45: (43) View through grate floor in façade. (44) Vent and depth of façade. (45) View out façade showing floor grate and metal blinds.
Stadtsparkasse Dusseldorf, Dusseldorf, Germany

We found the Stadtsparkasse Dusseldorf as we were walking the streets of Dusseldorf. It caught our eye because of the installation of the double skin facade. We stopped to take a picture and ask one of the construction workers which building this was and he said "Stadtsparkasse, Bank of Dusseldorf".

It was unclear when we were looking at the building how the double skin was going to work, as the louvers were facing down, as if to catch hot air rising on the surface of the building or letting cold air out of the building. For the louvers to work properly for natural cooling of the building, they would have to be placed at the top of each floor to let the warm air out.

That is the extent of the information that we were able to gather, although additional research should be continued to understand how this building is intended to operate.

European Patent Office, The Hague, The Netherlands

The naturally ventilated European Patent Office (EPO) in The Hague in the Netherlands was built in 1972, and is the tallest naturally ventilated building in the Netherlands. The building is adjacent to a sealed air-conditioned EPO office building, with approximately the same number of people, which is good for comparison. The building management noted that the complaints are three times higher in the sealed building.

Due to the thermal mass, it takes 4 days to heat up the building to uncomfortable levels, which works well, since the local climate typically has less than 3 days in a row of high temperatures. The thermal mass does have both carpet and ceiling tiles, both of which are designed not to diminish the effect of the thermal mass too much. The concrete is also used as an external shade, as you can see from the pictures taken from the inside. The concrete shading occurs at every floor except for the top floor of the lower building around the tower, which became an issue, as they had both less thermal mass and less shading, so they had to install air conditioning for the entire floor.

It is said that the naturally ventilated building creates a user-friendly environment, with increased user control and satisfaction. Although it was noted that sometimes papers do fly off of the desks with a heavy draft, and the high volume printers have some moisture problems with paper sticking.

The internal spaces, which were typically used for storage and meeting spaces, which do not have direct contact with the outer perimeter, used ceiling fans to increase the airflow. The other spaces that do not use purely natural ventilation include the air conditioned computer rooms and the top floor of the lower building. The air conditioning is user-controlled, which "helps people psychologically to feel more comfortable".

Pictures A-47,48,49: (47) Exterior view showing tower and low-rise. (48) View out of office showing operable windows and overhang. (49) Model of EPO complex.
ABN Amro, Amsterdam, The Netherlands

On our search for ING Bank headquarters, we came to the ABN Amro building just outside the A10 highway and near the Zuid station. Upon entering the building, we noticed a large atrium space. After asking the reception about the possibility of meeting with someone concerning the building and window usage we were given a very brief tour to one floor by an employee of the building group. We were not allowed to bring our cameras on the tour, but we were given some information pamphlets that had some additional pictures to describe how the building performs.

The only operable windows that the building has for the office spaces are small (8-10” square) windows. All of the windows have internal blinds between the panes of glass, keeping the solar gains from entering the office spaces, but allowing the solar gains on the window’s glass and frame. On the day that we visited, which was a mild day, some of the windows are open. It was noted by the employee that gave us the tour that the windows are purely used on an individual office basis, and are not used as a whole building cooling strategy. The building uses "cool ceilings" as the cooling and heating strategy. Additionally we were told that there is an aquifer on site, although we did not see it nor have we found it in the literature (long term storage of energy for peak hours).

The public spaces of the complex were also designed to be a friendly environment, with quick access to the train and subway as well as a large number of bike parking spots to ease commuter concerns. There is a pond at the side of the building as well as courtyard spaces and landscaping to look less commercial.

ING Bank Headquarters, Amsterdam, The Netherlands

The ING Bank head office is one of the early designs that included many environmentally conscience features, including natural ventilation. Originally the NMB headquarters, this building became the headquarters of ING Bank after it took over NMB. Since this building was built in the mid 1980's, the office environments have changed, which likewise has changed the use of the building, such that they do not currently use natural ventilation as a cooling strategy. It was decided that they would keep all windows closed and condition the air, since the cooling load became too much for the natural ventilation strategy, with almost twice an many people as the building was designed for as well as many more computers than in the 1980's.

First, the design feature which made it possible for natural ventilation during the early years of operation include external shading, operable internal and external windows, atriums, and thermal mass. There are operable window to most mid and small sized windows to the outside and atrium spaces, which allow for cross ventilation through the office and stack ventilation up through the atrium and through the roof of the atrium.

Without the use of the operable windows, the external shading and thermal mass can only help the cooling strategy, which has become air conditioning. The building manager has a concern with the operation of the building, since they can only generate 80% of the energy needed to operate the building, requiring them to buy energy from the local utility. With close to 75% of the energy load being the cooling load, there is significant reason to minimize the cooling load so that they do not need to buy additional generators. Possible solutions include night ventilation, night cooling storage for peak loads, or decreased building population and computer equipment.

Strathclyde University Dormitory, Glasgow, Scotland

After leaving a meeting at the University of Strathclyde, we decided to take a quick look around campus and see the new energy efficient student residence halls. We observed occupants entering student residences on a cool to mild rainy day. As they entered the room, they opened the window, apparently for fresh air and view. In addition to the window, light was able to penetrate the wall through clear insulation glass wall. These can be seen in the picture as the foggier glass that is not operable.

Each façade on the residence hall was designed individually and has a different design. The north façade has more brick, while the south facade has more glass on the wall.


Pictures A-57,58: (57) View of open operable window located between insulated glass wall. (58) Operable window open inward as a door.
Maternity Hospital & older buildings, Glasgow, Scotland

In Glasgow, Scotland there are many older buildings that have operable windows and chimney stacks, and newer buildings that use operable windows and air conditioning. The older buildings have a very classic design for the windows, and height changes to promote hot air movement away from the occupied spaces.

The maternity hospital is a great example of a modern addition onto an older classic design building. The older building has a lot of thermal mass and consistently large operable windows, with a newer addition that does not have any true thermal mass, but has more non-operable glass. The result is that the two-floor addition required air conditioning units.

On a cool rainy day, there were quite a lot of the windows open in a more modern building. And there were operable windows in the mall in Glasgow that run along the building under the overhang. Some of the windows were open when we entered, but were closed when we left shortly thereafter.

Pictures A-59,60: (59) Maternity hospital with addition. (60) Modern building with operable windows.

Pictures A-61,62,63: (61) Operable windows under overhang of mall entrance. (62-63) Glasgow skyline with operable windows and height variation to induce air movement.
Inland Revenue Service, Nottingham, England

The Inland Revenue Service Nottingham Complex, designed by Michael Hopkins and Partners, has a nice architectural look, some good ideas for natural ventilation, but some comfort problems. The first receptionist that we spoke with said "it was a horrible ventilation system with no air conditioning," and that people on the top floor get too hot.

The natural ventilation for the lower floors are intended to work as a stack airflow system, with the air inlet through the exterior walls of the office and the outlet through the stairwell stack at each building corner. The top floor ventilation is intended to work as a short stack airflow, with the inlet at the exterior wall and the outlet through operable openings in the roof. Each office has one large operable window the size of a door that opens to the exterior, and a door that opens to the hallway. For the ventilation to work through the stack, both the window and the door need to be open. We noticed that for privacy reasons, that most offices had their door closed to the hallway.

One detail that could be used to promote natural ventilation is the wavy slab ceiling, which runs the width of the building. The ceiling should be a natural fit to move hot air from the peak of the ceiling across and out of the building with cross ventilation, but the building is partitioned such that cross ventilation is not allowed at the ceiling level. This does not move out the hottest air, making the ventilation system less efficient.

The stack stairwell, which is intended to promote airflow from the lower level floors, has an operable fabric roof membrane, which opens upward mechanically when the building gets too hot. The stacks do have too much thermal mass, which moderates the air temperature and decreases airflow when the people need the increased airflow. Fans are used in the offices to increase airflow mechanically.

Pictures A-64,65,66: (64) Stairwell stack. (65) View up stairwell showing airflow path. (66) Exterior view showing wavy ceiling and operable door windows.
The University of Nottingham, Nottingham, England

The University of Nottingham's Jubilee Campus is their "new campus for the new century". Designed by Michael Hopkins and Partners, it incorporates aspects of natural ventilation and sustainable building approaches, and was opened in October 1999. The campus has a nice feel of innovation and sensible design.

This campus has had some growing pains that need to be resolved, including a pond that was having its seals reworked around the perimeter, since it was flooding into the buildings. In addition to the water problems, there have been heat transfer problems on the windows facing the pond, as the overhang does not give enough external shading from the solar heat gains in the summer. These same windows were getting colder than expected in the winter, since they offer very little insulation.

Beyond these problems, the campus was very nice and functioning well on the mildly cool day that we visited. With a combination of air inlets near ground level, air outlets near the ceiling level, and a large amount of thermal mass, the atriums have good design for comfort, and have been able to maintain comfort well. The design detail that caught our attention the most is the stack and wind sail combination. The wind sails, which we observed rotating with the changing wind direction is able to use increased airflow with the proper direction to pull hot air from the stack.

Pictures A-70,71: (70) Grass roof and operable windows. (71) View up into wind sail.

Pictures A-72,73: (72) Exterior view of campus. (73) View of inner campus showing overhang.
Queens Building, Leicester, England

The Queen's Engineering Building at DeMontford University, located in Leicester England was completed for university use in August of 1993 and was designed by Alan Short and Brian Ford of Short Ford Associates. The building is a combination of offices, lecture halls, classrooms, and laboratories, all of which use natural ventilation to assist in creating a comfortable climate. In fact, only 2 rooms in the entire building use air conditioning, one laboratory and one equipment room.

The major type of natural ventilation used is stack ventilation to bring the warm air up and out of the different rooms to a series of large stacks above the roof. The first floor classrooms, with a capacity of 54 students have 2 outlets at the ceiling level to the stacks, while having 4 inlets through manually operable windows at the outer wall.

The lecture halls each have air inlet through the outer wall and exhaust air up through the stacks as well. The difference is how the inlet and outlet are placed within the room's configuration. One of the lecture halls has the teaching stage located on the exterior wall with the amphitheater style seating located under the stacks. The other lecture hall however had a slightly more complicated design, with the placement of the air inlets under each level of the amphitheater seating creating a displacement ventilation scheme, while the outlet to the stack is up and behind the stage.

The laboratories are ventilated through atrium outlets and various openings at the external wall. The laboratory spaces have roof windows controlled by the building management system (BMS) to exhaust the hot air out. The air inlets range from small openings in the engineering laboratory to minimize noise pollution to the neighboring community, to more windows in the laboratories facing the Universities property.

At the top floor, above the lecture halls, the computer lab also has operable roof windows, but they were just recently fixed after not being operable since the first year the building was in use. Without the use of the windows at the top of the room, the room has maintained comfort through the use or windows along the side walls to the exterior, using single sided ventilation. The office spaces, which are for professors, teaching assistants, and staff, have been the area of highest complaint. This is also at the top level, near the computer lab. We were unable to do a walk through of this space since it is a restricted area as a no student zone. We were told the office area had operable skylights installed after the reports found that it had the most comfort concerns.

Another issue that was raised on our tour was that sometimes there has been too much user control or the windows or heating. Too much control happens in a case when the user is not aware of how to operate the space that they are in, or when the user decides to change settings to make other users uncomfortable. One case of not operating the space properly is when opening the stacks for ventilation of the classroom spaces. Since the classrooms have two outlets at either end of the room, a draft could occur across the room during the winter if the stacks are opened improperly, to create one as an inlet and one as an outlet.
The Institute of Energy and Sustainable Development did a case study in 1991 concerning naturally ventilated spaces in the then “new building for the School of Engineering and Manufacture at De Montfort University that was designed to be naturally ventilated, as far as possible.” In the analysis used for understanding the natural ventilation, computer simulations for one day were used to first identify the largest influences in the design. Design optimization was then completed with both a physical model and refined computer simulations. “Finally, the occurrence of warm conditions in the auditoria was studied for a typical year.”

Pictures A-74,75,76: (74) Seating in auditorium allowing air movement under the seats. (75) Ceiling operable windows. (76) Concrete and glass block walkway.

Pictures A-80,81: (80) Air transfer grill in classroom. (81) Another operable window set.

Pictures A-82,83: (82) Operable windows near ceiling. (83) Air outlets by means of stack in auditorium.
Pearson Education, Harlow Town, England

The Edinburgh Gate building, which is occupied by Pearson Education seemed to be one of the best operational naturally ventilated buildings that we visited. We had a nice tour with the building manager, John Fessey. The natural ventilation occurs through a combination of external operable windows, an open floor plan, non-operable internal louver transfers, and atriums at each section of the building. It was noted that in the creation of this building, it was important "to be environmental, use renewable resources, have an effective lifecycle, but first the building needed to be commercially sound." In fact the financial backing for the project required a backup plan if the NV did not work. As a result of the design considerations, "in 1995 it was the most environmentally sound commercial building."

The building does have both heating and cooling that help maintain a comfortable and controlled climate. There is air conditioning in the computer room and the top floor, which has a kitchen, board rooms, and spaces that typically do not use natural ventilation. The top floor also has mechanical ventilation to assist with moving the hot air out. The top floor cafeteria is only conditioned starting at 11AM, and only if needed. Controls for the air-conditioned spaces are based on occupancy, such that when it is occupied there is a smaller temperature bandwidth to maintain more comfort.

Since the building does need to use energy, for heating, cooling, lighting and equipment, first they use the energy that is stored in the building before starting the system. In addition, they use ice storage of 200 KW which is stored every night when they can use off peak energy. In winter it is used to help balance loads, while in the summer it is used during the peak energy load hours. Compared to the old building, which the company moved from, this building is able to house 70% more people, with 50% more square footage, but 40% less energy use. This building has had a goal of using as little as 3 gigawatt hours, but they have not been able to reach it yet, although they do come close.

The first part of the natural ventilation that you notice as you visit the Pearson Education building is the series of external light shades with 2 small operable windows for each, one on top (which opens inward) and one on the bottom (which opens out), with larger non-operable windows below. These small windows are fully open or fully closed. If you put it between, you have the chance that it may slam open or shut with the wind, this is one disadvantage that we saw compared to other buildings that we viewed.

The typical office open into the atrium has a door, operable window toward the middle, non-operable window above, and wooden louvers that are set in place and open between the spaces. In addition, the office plan is quite wide, like many office buildings in the United States, but the floor plan is open and vertical dividers run from outer wall to atrium, so that air can flow through the floor plan with little resistance. In fact, the situations where closed office space is required the door has an automatic opener, such that the user of the space would have to shut the door, otherwise it would remain open. To maintain the use of airflow through the floor plan, they are limited to 25-30% cellularization of floor space.
There are 3 atria (One near the railway, one in middle, and one near the highway) that help to connect each office space to more comfortable air, either outside air or atrium air. The Atrium remains open to allow for the natural ventilation to bring in cool air until the atrium gets below 20 Celsius. For the winter, there is an under floor heating in the Atrium, allowing heat to rise up through the floor plan. BMS takes 5-day data to decide whether it is Summer or Winter, so that both the heating and cooling do not operate together. To moderate the conditions and temperature fluctuations, there is a significant amount of thermal mass, especially as the horizontal elemental, such as the floor.

The top windows for each atrium are automatically controlled by the building management system and the two weather stations on the roof. With the openness of the floor plan, open louvers, and automatic windows, this building has the ability to use night cooling. However, they do not use night cooling since there were too many complaints of offices being too cold when they came to work in the morning. Also with the open plan, there is a concern for noise pollution disrupting the work, but it was noted that the people that complained about the noise were typically those who worked the flex hours, and therefore did not have the constant office noises as white noise.

Additional design friendly features include:
- Unisex toilets
- Automatic turn off for electricity
- Automatic windows at ground level to allow fresh air to push smoke out of the atrium

Pictures A-84,85,86: (84) Operable windows with rolling blinds. (85) Fixed louvers for air transfer between the office and atrium. (86) Fixed blind on exterior.
Pictures A-87,88: (87) View of office from inside atrium. (88) Operable windows at perimeter and circular mechanical outlets on ceiling.

Pictures A-89,90: (89) Open stairwell in atrium. (90) Operable windows at perimeter and external landscaping on roof deck.
The Building Research Establishment’s Environmental Building is a good example of several different approaches to sustainable building and natural ventilation design. The building uses stack ventilation from the office spaces and up through the metal stack chimneys to promote airflow when there is minimal wind. When wind is available, air is able to flow through the office spaces by means of cross ventilation, with operable windows and a wavy slab ceiling.

To increase the ability for the building to use natural ventilation for climate control, gray-green glass and external blinds help to minimize the cooling load by keeping solar heat gain from the conditioned space. Additionally the building uses balconies over the entrance atrium space to keep the solar gains out of the entryway. The office loads are minimized, as lighting in the office space is able to dim, while maintaining 300-350 lux, to use more natural light and less energy and heat gain from the artificial lighting.

The ventilation stacks performed differently than expected due to the increased thermal mass at the sides of the ventilation stack. With both glass block and concrete near the stacks, there is less air movement during the day with delayed heat gain with increased thermal mass. In the night, however, there is the ability for additional night cooling with higher temperatures within the stack compared to outside, creating increased air flow within the stack. Thermal mass was also used within the office space to help moderate room conditions, with more surface area on the wavy concrete ceiling, as can be seen in the interior pictures. In addition to the office space, this building has an auditorium space which uses natural ventilation through cross/stack ventilation. The air flows from near the floor in the back of the auditorium to a black grille in the ceiling.

Groundwater is also used to condition the building, as it flows through tubes in the slab to allow for chilled thermal mass throughout the summer. In the winter, heated water flows in place of the cold water to help keep the office space warmer. The increase in thermal mass through the ceiling is important since the office floors have carpet covering their thermal mass.

It has been estimated that the employees that work in this building have approximately the same productivity in the winter and about 20% more in the summer, when natural ventilation is best used for energy efficiency and increased user comfort. This building also used bricks from a building being torn down to follow through with the sustainable building approach.
Pictures A-91,92: (91) Exterior view. (92) Glass block and aluminum stacks and horizontal shading devices.

Pictures A-93,94,95: (93) Exterior view with solar panels and overhang. (94) Air outlet through ceiling. (95) Wavy thermal mass ceiling with view of external shades.

Sainsbury Greenwich, Greenwich Peninsula, England

"A store for the 21st century"

Sainsbury's at Greenwich Peninsula was the last of the buildings for us to visit while on our trip in Europe. Just down the road from the Dome 2000, it was created as part of a community development project that has changed an "industrial wasteland" into energy efficient homes, offices and even this supermarket.

Outside the entrance, there are two sets of photovoltaic solar energy collectors as well as small windmills above them to collect wind. Both of these are part of creating an image of being energy efficient, even though these actually do nothing more that provide enough energy to light the signs on the two poles that hold the solar and wind collectors. But, as you enter the store you notice a difference. With the majority of the light in the supermarket coming from the skylights from the outside, you can tell that they can save energy throughout most of the day by not using the lights on the ceiling (as they were off when we were there). The other lighting that was provided for the customers was directly in the display racks, as in any other supermarket.

It is also noted in the literature that we picked up at the store that the building uses passive ventilation in addition to the passive lighting that was so noticeable. Additional energy efficient features include an earth mound around the perimeter of the building, to keep the exterior of the buildings walls warmer in the winter, as well as combined usage of water for product cooling, building cooling, toilet flushing and landscape irrigation.

Appendix B: Contact List - Naturally Ventilated Buildings

Denmark
Windowmaster
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Email: sh.dk@windowmaster.com

Germany
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Mr. Loter (Gartner Company)
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Mr. Muldolf (Gartner Company)
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Victoria Insurance (Dusseldorf)
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Edinburgh Gate/Pearson Education Headquarters
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   Email: John.Fessey@pearsoned-ema.com

BRE (Building Research Establishment)
Tony Johnson (Project Manager in Environmental Best Practice Division)
   Tel: 01923 663539
   Fax: 01923 664097
   Email: johnsont@bre.co.uk
Other contact: Steve Moncress; tel: 01923 664000

Cambridge University-Math and Science Center
Contact: Hillary Bennett
   Tel: 01223 337733 ext. 66820
Appendix C: Buildings & Building Designs with Natural Ventilation—
Building Readings

Black Rock Forest Center for Science & Education, Cornwall, NY:<10>
Oblong east/west shape, mostly south facing windows, low-e/argon glazing, daylighting, highly insulated walls, SIP roof, geothermal heat pumps, variable speed fans & pumps, heat recovery, 20 cfm/ person ventilation rate, CO2 sensors, natural ventilation, efficient lighting with occupancy sensors, 43 to 49% energy savings over a code complying building.

Building Type: Low-rise science & education center
Building Location Type: College Campus

Brainbridge Island City Hall, Brainbridge Island, WA:<10>
Daylighting, optimized natural ventilation, non-toxic & non-ozone depleting materials, certified wood, recycled & reused materials, non-toxic finishes, porous asphalt paving.

Building Type: Low-rise city hall
Building Location Type: Rural
Contact: Claudine Manio, Miller/Hull, 206-682-6837 ext 244, Cmanio@MillerHull.com

Building 850 Naval Construction Battalion Center, Port Hueneme, CA:<10>
1998, 45% energy & water savings compared to existing building, major renovation & addition to existing building, daylighting, shading, photovoltaics, solar space & domestic hot water heating, high efficiency lighting with dimming/ photo sensors/ occupancy sensors, natural ventilation, natural gas heat pump air conditioning, underfloor air distribution, heat recovery from air conditioning system, high efficiency pulse boilers, gray water reuse, rainwater harvesting, water conserving irrigation, IAQ monitoring, recycled & reused building materials, low toxic materials.

Building Type: Low-rise office and computer facility
Building Location Type: Military
Contact: Scott Ellinwood Associates (architect), http://www.ctg-net.com/Projects/Navy

Chesapeake Bay Foundation Headquarters, Annapolis, Maryland:<10>
Fall 2000, LEEDTM Certified, energy use is 50% less than ASHRAE 90.1-1989, existing footprint, geothermal, photovoltaics, natural ventilation, daylighting, solar hot water, passive solar, dessicant dehumidification, composting toilets, non-CFC/HCFC SIPs, recycled content /recyclable/local/low-VOC/low embodied energy materials, rainwater catchment, native plantings, porous paving, bicycle storage.

Building Type: Low-rise office building and conference facility
Building Location Type: Rural
Columbia University's Lamont-Doherty Earth Observatory, Palisades, NY:<10>

Natural ventilation, daylighting, temperature sensor operated clerestory windows, large overhangs, deciduous tree shading, operable windows, open offices, occupancy sensor lights, building management system.

Building Type: Low-rise office building and conference facility
Building Location Type: Rural
Contact: Charles Blomberg of Rafael Vinoly Architects, 212-924-5060, www.rvapc.com

David L. Lawrence Convention Center expansion, Pittsburgh, PA:<10>

Partially reuse existing structure, urban infill, natural ventilation, low temperature air delivery, displacement ventilation, raised floor air supply plenum in meeting rooms, daylighting, spraying water evaporative cooling of roof, environmentally preferred materials, ice storage, geothermal cooling, grey water recycling.

Building Type: Low-rise convention center and offices
Building Location Type: Urban
Contact: Rebecca Flora of Green Building Alliance, 412-431-0709
Contact: Dori Landry, Burt Hill Kosar Rittelmann Associates, 202-333-2711

Delridge Community Center, Seattle, WA:<10>

1995, energy efficiency, low-flow plumbing fixtures, energy management control system, natural ventilation, operable windows, energy efficient building orientation, daylighting, recycled content materials.

Building Type: Low-rise community center
Building Location Type: Suburban
Contact: Boyle-Wagner Architects, 206-382-9651

Disney Conservation Learning Ctr., Disney Wilderness Preserve, Kissimmee, FL:<10>

Natural ventilation, operable windows, east/west long axis, oak tree shading, 5' overhangs, low-e/double glazed windows, integrated photovoltaics, geothermal heat pump, zoned HVAC, high efficiency lights, daylighting, environmentally preferred materials, low-VOC paints & stains, wood from sustainably managed forest, rainwater harvesting, construction waste recycling.

Building Type: Low-rise learning, administrative & laboratory facility
Building Location Type: Rural
Contact: Geoff Meyer, Cooper Johnson Smith Architects, Inc., 813-273-0034
University California, Environmental Science & Management, Santa Barbara, CA:<10>

2001 completion, LEED certified, daylighting, passive solar heating/cooling, operable windows, natural ventilation, energy efficient lighting w/ motion&photo sensor controls, most energy efficient laboratory ventilation available, multi-building virtual chilled water loop, toilets use reclaimed water, recycled materials, certified wood, construction waste management, native landscaping, reclaimed water irrigation, permeable grass paving.

Building Type: Low-rise office, laboratory, & conference building
Building Location Type: College Campus
Contact: Zimmer Gunsul, Frasca Partnership, 503-224-3860

Michigan Tech. Univ., Environmental Sciences and Engineering, Houghton, MI:<10>

HVAC heat recovery, improved indoor air quality strategies (source control, ventilation), daylighting, supplementary passive ventilation, material recycling chutes, recycled content materials, modular size offices and labs, building materials recycled during construction.

Building Type: Mid-rise education, research & office building
Building Location Type: Urban
Contact: SHG, Inc., 313-983-3600, info@smithgroup.com

Environmental Technology Center Sonoma State Univ., Rohnert Park, CA:<10>

Fall of 2000, "smart building" control technologies, environmentally-sensitive materials, reused/sustainably harvested wood, natural ventilation, passive solar heating/cooling, thermal mass, heavily insulated envelope, advanced window systems, daylighting, PV, digital communication systems, water-efficient landscaping.

Building Type: Low-rise education, research & office building
Building Location Type: Suburban
Contact: Sonoma State Univ., 707-664-2306

Montana State University, EPICenter, Bozeman, MT:<10>

2000, still in design, Passive ventilation, passive heating and cooling, daylighting, fuel cells, photovoltaic panels, rainwater harvesting, solar aquatic wastewater treatment, sustainable materials, advanced glazing, intelligent building system controls, going for platinum LEED.

Building Type: Low-rise education, research & office building
Building Location Type: Semi-rural
Contact: Kath Williams of MSU, 406-994-7713
Frye Art Museum, Seattle, WA:<10>

Major renovation, daylighting, overhangs/recesses/baffles/vertical fin sun shading, natural ventilation, operable windows.

Building Type: Low-rise art museum
Building Location Type: Urban
Contact: Olson Sunberg Architects, 206-264-3730

Gap, Inc. Office Complex, San Bruno, CA:<10>

1997, 30% more energy efficient than code complying, 8 year simple payback, raised floor supply plenum, fan-assisted natural ventilation, operable high-performance windows, energy-efficient lighting, manual sun shades, living roof, sustainably harvested wood, daylighting, low toxicity paints & adhesives.

Building Type: Low-rise office building
Building Location Type: Suburban
Contact: William McDonough, 804-979-1111

Hawaii Convention Center, Honolulu, Hawaii:<10>

1996, daylighting, natural ventilation, native landscaping.

Building Type: Low-rise Convention Center
Building Location Type: Urban
Contact: Kristy Kimaura, Mark Reddington of LMN Architects, 206-682-3460

Herman Miller SQA Building, Holland, MI:<10>

1997, re-use of old industrial site, 65% less water costs, 18% less electricity costs, 7% less natural gas use, worker productivity increase vs. former building, daylighting, energy-efficient glazing / ventilating, photo & motion sensor dimming lighting, passive heating & cooling environmentally preferred materials, construction waste management plan.

Building Type: Low-rise furniture factory, warehouse & headquarters building
Building Location Type: Rural
Contact: William McDonough + Partners, 804-979-1112

Kansas City Zoo, Deramus Education Pavilion, Kansas City, MO:<10>

Recycled copper roof, passive solar design, natural ventilation.

Building Type: Low-rise education/ display building
Building Location Type: Zoo
Contact: Berkebile Nelson Immenschuh McDowell Architects, 816-474-6910
Lawrence Marx Resource Center, Hood College, Frederick, MD:<10>

Active solar water heating, passive solar heating/cooling, daylighting, natural ventilation.

Building Type: Low-rise apartment, laboratory, office, computer center building
Building Location Type: College Campus
Contact: Contact: Dori Landry, Burt Hill Kosar Rittelmann Associates, 202-333-2711

Natural Resources Defense Council, Santa Monica, CA:<10>

LEED Platinum rating targeted, 40-50% reduction in energy use below Title 24. renovation and addition, daylighting, natural ventilation, high efficiency HVAC, under floor air distribution, high efficiency lighting with occupancy sensors and daylight sensors, optimized building envelope with spectrally selective glazing, operable windows, low-energy office equipment, improved interior air quality via source control.

Building Type: Low-rise office building
Building Location Type: Urban
Contact: Gregg Ander, AIA at Southern California Edison, 626-633-7160

Newport Coast Elementary School, Newport Beach, CA:<10>

Projected energy reduction: 43% below a minimally compliant building as measured by the California Energy Code (Title 24) daylighting, increased wall and roof insulation, direct/indirect high-efficiency fluorescent lighting w/ stepped switching & occupancy sensors, efficient heat pumps, fan-assisted natural ventilation, solar thermal domestic hot water system.

Building Type: Single story school
Building Location Type: Suburban
Contact: Deborah Weintraub, AIA of Southern California Edison, 626-633-7191

Vermont Law School, Oakes Hall, South Royalton, VT:<10>

Fall 1998, 57% less fuel / 35% less water / 25% less electricity use than typical, 1 watt/sf lighting system, photoelectric & occupancy sensored lighting controls, independent occupancy sensored controlled ventilation, enthalpic/desiccant energy recovery & dehumidification wheel, composting toilets, environmentally preferred materials, sustainable managed forest wood, operable fiberglass super windows, highly insulated stress skin panel.

Building Type: Low-rise Classroom & student lounge
Building Location Type: College Campus
Contact: Truex Cullins & Partners Architects, 802-658-2775, 800-227-1076
Ogden Nature Center, Ogden, UT:<sup>10</sup>

1995, passive solar heating/cooling, under-floor hot water heating, daylighting with shading & light shelves, energy efficient light fixtures controlled with occupancy sensors & timers, natural ventilation, resource efficient/ recycled/ salvaged materials, low-VOC/toxic materials, building sited to minimize natural habitat disruption.

Building Type: Low-rise visitor & administration center
Building Location Type: Rural
Contact: Carl Palmer of Ogden Nature Center, 801-621-7595, Sanders Herman Architects

Patagonia Distribution Center, Reno, NV:<sup>10</sup>

60% energy savings over typical, daylighting, light shelves, tracking skylights, high-efficiency lighting, passive ventilation, nighttime flush cycle, highly insulated building envelope, passive heating/cooling, water-efficient plumbing fixtures & irrigation, environmentally preferred materials, restoration of site ecosystems, xeriscaping, biofiltration swales & detention ponds.

Building Type: Low-rise office & distribution center
Building Location Type: Rural
Contact: The Miller/Hull Partnership, 206-682-6837

Real Goods Solar Living Center, Hopland, CA:

1996, Energy efficient envelope, passive ventilation and cooling, natural materials, daylighting, passive solar heating, photovoltaics, wind power generation, sustainable landscaping.<sup>10</sup>

Architect: Van der Ryn Architect
Climate/Site Analysis: Adam Jackaway
Owners: Real Goods Trading Corporation
Contact/Photo Credit: Van der Ryn Architects, 415-332-5806
Web Site: www.vanderryn.com
Location: The center is located in Sanel Valley near Hopland, California off of Route 101, a site that was once a landfill dump.
Occupancy/Use: Retail and a small area of business offices.

Energy Efficiency Features: Building orientation, a glazed south wall of low-e insulating glass, limited windows facing east and west, trellises, roll-up hemp awnings, and overhangs all mitigate solar gain and glare. Daylighting is enhanced with light shelves, light colored surfaces, a shallow floor plan, a curved building section, and clerestory windows. The light shelves are hinged to act as night-time insulating window panels. Cooling and ventilation is assisted by a white HypalonTM roof; a ventilated roof
assembly; the building shape; operable clerestory windows working with low air intakes; thermal mass floors, walls and columns; grape arbors with a fountain and a drip/misting ring at the entrance; and solar powered evaporative coolers. The nearby Feliz Creek canyon provides a natural wind venturi for the wind generator. Of the average 100 kwh/day the facility uses, 70-80% is supplied by the on-site renewable energy system.

Rio Grande Conservatory, Albuquerque, NM:<10>

90% less energy, than comparable facility, selective glazing as per orientation & need, thermal mass, natural ventilation, passive solar heating/cooling, daylighting.

Building Type: Low-rise enclosed botanical gardens
Building Location Type: Rural
Contact: Mazrea Riskin Odems, Inc., 505-988-5309

Shippensburg Univ., Shippen Hall & Elem. School Training, Shippensburg, PA:<10>

30% less energy use than ASHRAE/IES 90.1 at addition, heat recovery air-handlers, separate ventilation & conditioned air, underground duct system, passive solar heating/cooling, operable windows, thermal mass, triple glazed/low-e/argon-filled/U=0.29 windows, highly insulated building envelope, daylighting, 0.9 W/sf average high efficiency lighting, occupancy & light-level lighting controls, high-albedo roofing, environmentally preferred materials, waterless urinals, pervious parking, building commissioning, construction waste management & IAQ plan.

Building Type: Low-rise education & lab building
Building Location Type: College Campus
Contact: Design 7, 717-540-5106 or 717-233-6320

Thoreau Center for Sustainability, San Francisco, CA:<10>

Architect: Tanner Leddy Maytum Stacy Architects
MEP Engineer: Flack + Kurtz
Lighting Design: Architectural Lighting Design
Owners: Thoreau Center Partners, National Park Service
Contact/Photo Credit: Richard Barnes, 415-550-1023
Occupancy/Use: Office space for Tides Foundation, the Energy Foundation, Institute for Global Communications, and sixteen other with sustainable and/or environmental activities.

Energy Efficiency Features: The mechanical and electrical systems of the building where kept simple and were designed to take advantage of the local benign climate and the narrow width shapes of the building. The new renovations attempted to maximize the existing daylighting attributes of the existing structures. The perimeter offices were enclosed by seven foot high aluminum and glass partitions that allowed natural light
penetration. Natural ventilation was enhanced by these same low partitions, existing operable windows, ceiling vents and attic vents. Photovoltaic panels are used as a sun screen above the entrance skylight. The mechanical systems performance was increased through the use of high efficiency/low temperature radiators with local thermostat controls, high efficiency motors, variable speed pumps & drives, and resetting of hot water heating temperatures depending on outdoor air temperatures. Energy use was calculated to be one-third of a standard non-energy efficient building.

University of Washington, Computer Science & Engineering Building, Seattle, WA:  
Planned completion 2003, daylighting, exterior sun shades, translucent panels, sun controlled skylights, natural ventilation, computer energy modeling utilized.

Building Type: Mid-rise office and laboratory building  
Building Location Type: Urban  
Contact: Kristy Kimaura, Mark Reddington of LMN Architects, 206-682-3460

Utah Department of Natural Resources:  
DOE2, passive orientation and ventilation, R28 walls, low-e, daylighting, dimmable T8s and sensors, 4-stage HVAC with evaporative cooling, recycled lumber, xeriscaping, 43% savings vs typical, cost premium of 3% for a 6 yr payback.

Building Type: Low-rise office building  
Contact: Burke Miller, Environmental Educator, David Brems (architect), 801-521-8600

Van Atta Office, Santa Barbara, CA:  
Average energy consumption is 30% lower than a conventional energy code (Title 24) compliant design, urban infill site, passive design elements to optimize daylighting and natural ventilation, thermal mass and enhanced stack ventilation, high-efficiency heat pumps with two speed compressors, air filtration, indirect fluorescent lighting with zoned controls in relationship to daylighting elements, and a palette of resource efficient materials.

Building Type: Low-rise office building  
Building Location Type: Urban  
Contact: Gregg D. Ander, AIA. of Southern California Edison, 626-633-7160
Appendix D: Natural Ventilation Tool Equations

**TEMPERATURE:**

Thermal Mass Temperature

\[ T_{\text{conc-1}} - (h_{\text{conc}} \times A_{\text{conc}} \times 3600 \text{ seconds}) \times (T_{\text{conc-1}} - T_{\text{room-1}}) / (M_{\text{conc}} \times c_{\text{conc}}) \]

Bulk indoor room temperature decision for natural cooling only

- If window type is “Optimized”, then \( T_{\text{noAC}} = T_{\text{optimized}} \)
- Otherwise if window is “Night”, then \( T_{\text{noAC}} = T_{\text{nightcool}} \)
- Otherwise if window is “Open”, then \( T_{\text{noAC}} = T_{\text{open}} \)
- Otherwise \( T_{\text{noAC}} = T_{\text{closed}} \)

Bulk indoor room temperature decision when mechanical air conditioning is possible

- If the temperature with the window closed is less than \( T_{\text{cool}} \) then set the temperature to \( T_{\text{window-closed}} \)
- Otherwise if the window type is “Night Cooling”, then if \( T_{\text{ACoff}} \) is less than \( T_{\text{night}} \) set \( T = T_{\text{night}} \)
- Otherwise if \( T_{\text{ACoff}} \) is greater than \( T_{\text{cool}} \) set \( T = T_{\text{cool}} \)
- Otherwise set \( T = T_{\text{heat}} \)

Indoor temperature if window is always open

- Maximum of \( [T_{\text{heat}}] \) & \( [T_{\text{open_calc}}] \)

Indoor temperature if window is always closed

\[ [(W_{\text{room}} + \text{Flow}_{\text{min}} \times \rho \times c_p \times T_{\text{out}} + h_{\text{conc}} \times A_{\text{conc}} \times T_{\text{conc}})] / (\text{Flow}_{\text{min}} \times \rho \times c_p + h_{\text{conc}} \times A_{\text{conc}}) \]

Indoor temperature if window is optimized

- Minimum of \( [T_{\text{open}}] \) & \( [T_{\text{closed}}] \)

Indoor temperature if window is in night cooling mode

- Maximum of \( [T_{\text{nightcool}}] \) & \( [\text{if not night cooling time } T_{\text{heat}}] \) & \( [\text{Minimum of } T_{\text{open_calc}} \& T_{\text{closed}}] \)

Calculation of Indoor temperature if window is open

\[ [(W_{\text{room}} + \text{Flow}_{\text{NV}} \times \rho \times c_p \times T_{\text{out}} + h_{\text{conc}} \times A_{\text{conc}} \times T_{\text{conc}})] / (\text{Flow}_{\text{NV}} \times \rho \times c_p + h_{\text{conc}} \times A_{\text{conc}}) \]

Indoor temperature if the mechanical air conditioning is turned off for the hour

- If there is no ventilation, (AC is forced on) then \( T = T_{\text{cool}} \)
- Otherwise if the windows are always open \( T = T_{\text{open}} \)
- Otherwise if the windows are always closed \( T = T_{\text{closed}} \)
- Otherwise if the windows are optimized \( T = T_{\text{optimized}} \)
- Otherwise \( T = T_{\text{nightcool}} \)

**AIRFLOW:**

Flow Decision

- If the ventilation mode is SSV, then \( \text{Flow}_{\text{NV}} = \text{Flow}_{\text{SSV}} \)
- Otherwise if the ventilation mode is CV, then \( \text{Flow}_{\text{NV}} = \text{Flow}_{\text{CV}} \)
- Otherwise \( \text{Flow}_{\text{NV}} = \text{Flow}_{\text{min}} \)

Single Sided Ventilation Flow

\[ C_d \times A_{\text{win}} \times \text{sqrt}(|T_{\text{out}} - T_{\text{noAC}}| \times g \times h_{\text{wind}} / T_{\text{noAC}}) + \text{Flow}_{\text{fan}} \]

Cross Ventilation Flow

\[ \text{Maximum of } [\text{Flow}_{\text{fan}}] \text{ and } [A_{\text{win}} \times \text{sqrt} (0.125 \times V_{\text{wind}}^2)] \]

Dean
**HUMIDITY:**

**Window and fan decision based on humidity**

- If the Humidity with the fan for the next hour ($\omega_{\text{fanON}+1}$) on is $\geq$ Maximum humidity ($\omega_{\text{max}}$), then turn the fan off (0), otherwise if the enthalpy with the fan on for the next hour ($h_{\text{fanON}+1}$) is greater than the enthalpy with the fan off for the next hour ($h_{\text{fanOFF}+1}$), then turn the fan off (0), otherwise turn fan on (1).

**Indoor humidity**

If the Fan is off, then take the minimum of: [Maximum Humidity ($\omega_{\text{max}}$)] and [Humidity calculated for the current hour($\omega_{\text{in}}$)], otherwise if the fan is on, take the humidity calculated for the current hour.

**Indoor humidity bracketing**

If the Inside Humidity from the previous hour is greater than the outside humidity of the current hour, then take the maximum of the Outside Humidity and Inside Humidity Calculation; otherwise take the minimum of the Outside Humidity and Inside Humidity Calculation.

**Indoor humidity calculation**

=Maximum of the [minimum humidity ($W_{\text{min}}$)] and $[(M_{\text{in}}+M_{\text{gen}}+M_{\text{ent}}-M_{\text{ex}})/\rho*V]$

**Indoor humidity calculation with fan on**

Maximum of the [minimum humidity ($W_{\text{min}}$)] and $[(M_{\text{in}}+M_{\text{gen}}+M_{\text{ent\_fanON}}-M_{\text{ex\_fanON}})/\rho*V]$

**Indoor humidity calculation with fan off**

Maximum of the [minimum humidity ($W_{\text{min}}$)] and $[(M_{\text{in}}+M_{\text{gen}}+M_{\text{ent\_fanOFF}}-M_{\text{ex\_fanOFF}})/\rho*V]$

**Indoor enthalpy**

$$[((\omega_{\text{in}})/(\omega_{\text{in}}+1))]*h_{\text{fg}} + \{1-[(\omega_{\text{in}})/(\omega_{\text{in}}+1)]\}*c_{p\text{AIR}} + [(\omega_{\text{in}})/(\omega_{\text{in}}+1)]*c_{p\text{WATER}}}*T_{\text{room}}$$

**Mass of the air**

$$[1-(\omega_{\text{in}})]*\rho*V$$

**Mass of the water in the air**

$$[(\omega_{\text{in}})]*\rho*V$$

**Mass of the water generated in the room**

=human generation times the number of people

**Mass of the water entering the room**

=Flow * 3600 seconds * $\rho$ * Humidity Outside

**Mass of the water exiting the room**

=Flow * 3600 seconds * $\rho$ * (Humidity Outside + Humidity Inside) / 2
COMFORT OUTPUT:

CDH (cooling degree hour) count
=If \( T_{\text{noAC}} \) is less than \( T_{\text{cool}} \), then return 0, otherwise \((T_{\text{noAC}} - T_{\text{cool}})\)

SOLAR: <32>

Equation of Time
= 9.87 * SIN(4 * PI * (day-81) / 364) - 7.53 * COS(2 * PI * (day-81) / 364) - 1.5 * SIN(2 * PI * (day - 81) / 364)

Local Solar Time
= Hour + (4 * ((Local Standard Meridian) – (Longitude)) + (Equation of Time)) / 60;

Solar Hour Angle
= ((Local Solar Time) - 12) / 4;

Declination
= 23.45 * SIN ( (360 * (Day + 284) / 365));

Solar Altitude
= ArcSIN((COS(Latitude) * COS(Solar Hour Angle) * COS(Declination)) + (SIN * (latitude) * SIN(declination)));

Solar Azimuth
= ArcCOS((SIN(Altitude) * SIN(Latitude) - SIN(Declination)) / (COS(Altitude) * COS(Latitude))) * ((Solar Hour Angle) / |Solar Hour Angle|);

Solar Available on the South Wall:
If the Solar Altitude is greater than 0 degrees and the azimuth is between -90 and 90 degrees, then the solar available is: \( = \text{COS(Altitude) * COS(Azimuth)} \)
Otherwise there is no solar available on the vertical south wall.

Solar Available on the West Wall:
If the Solar Altitude is greater than 0 degrees and the azimuth is between 180 and 360 degrees, then the solar available is: \( = \text{COS(Altitude) * COS(Azimuth)} \)
Otherwise there is no solar available on the vertical west wall.

Solar Available on the North Wall:
If the Solar Altitude is greater than 0 degrees and the azimuth is between 90 and 270 degrees, then the solar available is: \( = \text{COS(Altitude) * COS(Azimuth)} \)
Otherwise there is no solar available on the vertical north wall.

Solar Available on the East Wall:
If the Solar Altitude is greater than 0 degrees and the azimuth is between 0 and 180 degrees, then the solar available is: \( = \text{COS(Altitude) * COS(Azimuth)} \)
Otherwise there is no solar available on the vertical east wall.
ENERGY USAGE:

Calculation of sensible energy when mechanical air conditioning is possible
= If $T_{A\text{off}}$ is less than $T_{\text{cool}}$ then return 0, otherwise return the maximum of [0] and

$[\left(T_{\text{out}} - T_{\text{cool}}\right) * \text{Flow}_{\text{min}} * \rho * c_p] + \left[(T_{\text{conc}} - T_{\text{cool}}) * h_{\text{conc}} * A_{\text{conc}} + W_{\text{room}}\right]$  

Calculation of latent energy when mechanical air conditioning is possible
= Maximum of [0] and $[\text{Flow}_{\text{min}} * \rho * h_{\text{fg}} * (\text{hum}_{\text{out}} - \text{hum}_{\text{in}}) + W_{\text{human latent}}]$  

Energy
If the fan is on, then zero energy, otherwise if the fan is not on, then if the Inside Humidity is equal to the Maximum Humidity, calculate energy, otherwise if inside drybulb temperature is less than 71.6 F & 22 C, then if the inside enthalpy is less than 80% saturation enthalpy, then calculate energy, otherwise if inside enthalpy is less than the 80% saturation level at 23 C (73.4 F), then 0, otherwise calculate energy.

Energy Calculation
Take the maximum of [zero] and $[h_{\text{fg}} * \left(M_{\text{int}} + M_{\text{gen}} + M_{\text{ent \_fanOFF}} - M_{\text{ex \_fanOFF}} - M_{\text{comfort}}\right)/3600 \text{ seconds}]$
## Appendix E: Conversions, Data, Symbols and Terms

### Conversions used between SI and IP

<table>
<thead>
<tr>
<th>Convert from</th>
<th>Convert to</th>
<th>Multiply by</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy British Thermal Unit (BTU.)</td>
<td>Joule (J.)</td>
<td>1055</td>
</tr>
<tr>
<td>Time Hour (hr.)</td>
<td>Second (s.)</td>
<td>3600</td>
</tr>
<tr>
<td>Length Feet (ft.)</td>
<td>Meter (m.)</td>
<td>.3048</td>
</tr>
<tr>
<td>Velocity Knot</td>
<td>Meter per Second (m/s)</td>
<td>.5144</td>
</tr>
<tr>
<td>Temperature Fahrenheit (F)</td>
<td>Kelvin (K)</td>
<td>(F-32)*5/9 + 273.15 = K</td>
</tr>
<tr>
<td>Temperature Kelvin (K)</td>
<td>Centigrade (C)</td>
<td>K-273.15 = C</td>
</tr>
<tr>
<td>Pressure Inch of Hg</td>
<td>Pascal (Pa)</td>
<td>3377</td>
</tr>
<tr>
<td>Pressure Pound per square inch (psi)</td>
<td>Pascal (Pa)</td>
<td>6895</td>
</tr>
<tr>
<td>Mass Pound (lb.)</td>
<td>Kilogram (kg.)</td>
<td>.4536</td>
</tr>
<tr>
<td>Volume flow Cubic feet per minute (cfm)</td>
<td>Cubic meters per sec. (m³/s)</td>
<td>1/2119</td>
</tr>
<tr>
<td>Density Pound per cubic foot</td>
<td>Kilogram per cubic meter</td>
<td>16.02</td>
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</tbody>
</table>

### Data

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density of air</td>
<td>( \rho )</td>
<td>1.177</td>
</tr>
<tr>
<td>Specific heat of air</td>
<td>( c_p )</td>
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</tr>
<tr>
<td>Specific heat of thermal mass</td>
<td>( c )</td>
<td>980</td>
</tr>
<tr>
<td>Gravity</td>
<td>( g )</td>
<td>9.8</td>
</tr>
<tr>
<td>Heat transfer rate w/ thermal mass</td>
<td>( h_c )</td>
<td>variable (3)</td>
</tr>
<tr>
<td>Volume of room</td>
<td>( V_{room} )</td>
<td>variable (50)</td>
</tr>
<tr>
<td>Minimum IAQ air changes</td>
<td>( \text{ac/h} )</td>
<td>0.35</td>
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<tr>
<td>Minimum IAQ air flow</td>
<td>( \text{Flow}_{\text{min}} )</td>
<td>0.35* ( \frac{V_{room}}{3600} )</td>
</tr>
<tr>
<td>Air flow of fan</td>
<td>( \text{Flow}_{\text{fan}} )</td>
<td>variable</td>
</tr>
<tr>
<td>Temperature of fanned air</td>
<td>( T_{out} )</td>
<td>Outside temp.</td>
</tr>
<tr>
<td>Coefficient of performance</td>
<td>COP</td>
<td>variable</td>
</tr>
<tr>
<td>Cooling setpoint</td>
<td>( T_{cool} )</td>
<td>variable (300)</td>
</tr>
<tr>
<td>Heating setpoint</td>
<td>( T_{heat} )</td>
<td>variable (293)</td>
</tr>
<tr>
<td>Night cooling setpoint</td>
<td>( T_{night} )</td>
<td>variable (289)</td>
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<tr>
<td>Heat of Vaporization</td>
<td>( h_{fg} )</td>
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<tr>
<td>Humidity</td>
<td>( \omega )</td>
<td>variable (.0125)</td>
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<tr>
<td>Latent Energy of Human</td>
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<tr>
<td>Window discharge coefficient</td>
<td>( C_d )</td>
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<tr>
<td>Solar Heat Gain Coefficient</td>
<td>SHGC</td>
<td>variable (from 0 to 1)</td>
</tr>
<tr>
<td>Cooling degree hours</td>
<td>CDH</td>
<td>Variable</td>
</tr>
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### Symbols and Terms

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{cone}$</td>
<td>Temperature of the thermal mass surfaces (K)</td>
</tr>
<tr>
<td>$h_{cone}$</td>
<td>Heat transfer of thermal mass to air (W/m²°C)</td>
</tr>
<tr>
<td>$A_{cone}$</td>
<td>Surface area of thermal mass (m²)</td>
</tr>
<tr>
<td>$M_{cone}$</td>
<td>Total mass of effective thermal mass (kg)</td>
</tr>
<tr>
<td>$c_{cone}$</td>
<td>Specific heat of thermal mass (J/kg K)</td>
</tr>
<tr>
<td>$W_{room}$</td>
<td>Total loads produced in room (Watts) (excluding solar)</td>
</tr>
<tr>
<td>$T_{cool}$</td>
<td>Cooling setpoint (K)</td>
</tr>
<tr>
<td>$T_{heat}$</td>
<td>Heating setpoint (K)</td>
</tr>
<tr>
<td>$T_{night}$</td>
<td>Night cooling setpoint (K)</td>
</tr>
<tr>
<td>$T_{sup}$</td>
<td>Temperature of air flow supplied from a conditioned source (K)</td>
</tr>
<tr>
<td>$T_{out}$</td>
<td>Temperature of air flow supplied from outside (K)</td>
</tr>
<tr>
<td>$T_{room}$</td>
<td>Temperature of the room (bulk temperature) (K)</td>
</tr>
<tr>
<td>$T_{AC}$</td>
<td>Temperature in room while in AC mode (K)</td>
</tr>
<tr>
<td>$T_{ACoff}$</td>
<td>Temperature in room while in AC mode if AC is turned off (K)</td>
</tr>
<tr>
<td>$T_{ACopen}$</td>
<td>Temperature in room while in AC mode with the window open (K)</td>
</tr>
<tr>
<td>$T_{ACopencalc}$</td>
<td>Calculation of temperature in room while in AC mode with the window open (K)</td>
</tr>
<tr>
<td>$T_{ACclosed}$</td>
<td>Temperature in room while in AC mode with the window closed (K)</td>
</tr>
<tr>
<td>$T_{ACoptimized}$</td>
<td>Temperature in room while in AC mode with the window in optimized mode (K)</td>
</tr>
<tr>
<td>$T_{ACnightcool}$</td>
<td>Temperature in room while in AC mode with the window in night cool mode (K)</td>
</tr>
<tr>
<td>$T_{noAC}$</td>
<td>Temperature in room not capable of using AC (K)</td>
</tr>
<tr>
<td>$T_{noACopen}$</td>
<td>Temperature in room not capable of using AC with the window open (K)</td>
</tr>
<tr>
<td>$T_{noACopencalc}$</td>
<td>Calculation of temperature in room with the window open (K)</td>
</tr>
<tr>
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<td>Temperature in room not capable of using AC with the window closed (K)</td>
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<td>Temperature in room not capable of using AC with the window in optimized mode (K)</td>
</tr>
<tr>
<td>$T_{noACnightcool}$</td>
<td>Temperature in room not capable of using AC with the window in night cool mode (K)</td>
</tr>
<tr>
<td>$Flow_{sup}$</td>
<td>Air flow supplied from a conditioned source (m³/s)</td>
</tr>
<tr>
<td>$Flow_{fan}$</td>
<td>Air flow through a fan (m³/s)</td>
</tr>
<tr>
<td>$Flow_{min}$</td>
<td>Air flow required for minimum IAQ (indoor air quality) (m³/s)</td>
</tr>
<tr>
<td>$Flow_{sav}$</td>
<td>Air flow through a window with single sided ventilation (m³/s)</td>
</tr>
<tr>
<td>$Flow_{cv}$</td>
<td>Air flow through a window with cross ventilation (m³/s)</td>
</tr>
<tr>
<td>$\rho_{air}$</td>
<td>Density of air (kg/m³)</td>
</tr>
<tr>
<td>$c_p$</td>
<td>Specific heat of air (J/kg K)</td>
</tr>
<tr>
<td>$C_d$</td>
<td>Window discharge coefficient, variable that effects the airflow.</td>
</tr>
<tr>
<td>$A_{win}$</td>
<td>Area of operable windows (for air flow) (m²)</td>
</tr>
<tr>
<td>$A_{glass}$</td>
<td>Area of total glass (for solar heat gain) (m²)</td>
</tr>
<tr>
<td>$g$</td>
<td>Gravity (m/s²)</td>
</tr>
<tr>
<td>COP</td>
<td>Coefficient of Performance for a cooling system ($W_{output}/W_{input}$)</td>
</tr>
<tr>
<td>$hum_{in}$</td>
<td>Comfortable humidity level indoor</td>
</tr>
<tr>
<td>$hum_{out}$</td>
<td>Humidity level outdoor</td>
</tr>
<tr>
<td>$h_g$</td>
<td>Heat of vaporization</td>
</tr>
<tr>
<td>$W_{humanlatent}$</td>
<td>Latent energy created by an average person (W)</td>
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### Symbols and Formulas

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<thead>
<tr>
<th>Symbol</th>
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<tr>
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<td>m*kg/s²</td>
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<tr>
<td>Pressure</td>
<td>Pa</td>
<td>N/m²</td>
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<tr>
<td>Energy</td>
<td>J</td>
<td>N*m</td>
</tr>
<tr>
<td>Power</td>
<td>W</td>
<td>J/s</td>
</tr>
<tr>
<td>Density</td>
<td>ρ</td>
<td>kg/m³</td>
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### Fan Data

<table>
<thead>
<tr>
<th>Model #</th>
<th>Fan Size</th>
<th>Cost</th>
<th>Watt</th>
<th>ΔP (Pa)</th>
<th>CFM : m³/s</th>
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<td>$ 60.75</td>
<td>36</td>
<td>136.2</td>
<td>560 : 0.264</td>
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</table>
Appendix F: Glossary of Terms

Absolute Humidity - The ratio of the mass of water vapor to the volume occupied by a mixture of water vapor and dry air.

Absorption - The passing of a substance or force into the body of another substance.

Absorptivity - In a solar thermal system, the ratio of solar energy striking the absorber that is absorbed by the absorber to that of solar energy striking a black body (perfect absorber) at the same temperature. The absorptivity of a material is numerically equal to its emissivity.

Adiabatic - Without loss or gain of heat to a system. An adiabatic change is a change in volume and pressure of a parcel of gas without an exchange of heat between the parcel and its surroundings. In reference to a steam turbine, the adiabatic efficiency is the ratio of the work done per pound of steam, to the heat energy released and theoretically capable of transformation into mechanical work during the adiabatic expansion of a unit weight of steam.

Adjustable Speed Drive - An electronic device that controls the rotational speed of motor-driven equipment such as fans, pumps, and compressors. Speed control is achieved by adjusting the frequency of the voltage applied to the motor.

Air - The mixture of gases that surrounds the earth and forms its atmosphere, composed of, by volume, 21 percent oxygen, 78 percent nitrogen.

Air Change - A measure of the rate at which the air in an interior space is replaced by outside (or conditioned) air by ventilation and infiltration; usually measured in cubic feet per time interval (hour), divided by the volume of air in the room.

Air Conditioner - A device for conditioning air in an interior space. A Room Air Conditioner is a unit designed for installation in the wall or window of a room to deliver conditioned air without ducts. A Unitary Air Conditioner is composed of one or more assemblies that usually include an evaporator or cooling coil, a compressor and condenser combination, and possibly a heating apparatus. A Central Air Conditioner is designed to provide conditioned air from a central unit to a whole house with fans and ducts.

Air-Source Heat Pump - A type of heat pump that transfers heat from outdoor air to indoor air during the heating season, and works in reverse during the cooling season.

Ambient Air - The air external to a building or device.

Ambient Temperature - The temperature of a medium, such as gas or liquid, which comes into contact with or surrounds an apparatus or building element.

Anemometer - An instrument for measuring the force or velocity of wind; a wind gauge.

Angle of Incidence - In reference to solar energy systems, the angle at which direct sunlight strikes a surface; the angle between the direction of the sun and the perpendicular to the surface. Sunlight with an incident angle of 90 degrees tends to be absorbed, while lower angles tend to be reflected.

Angle of Inclination - In reference to solar energy systems, the angle that a solar collector is positioned above horizontal.

Annual Fuel Utilization Efficiency (AFUE) - The measure of seasonal or annual efficiency of a residential heating furnace or

Array (Solar) - Any number of solar photovoltaic modules or solar thermal collectors or reflectors connected together to provide electrical or thermal energy.

ASHRAE - Abbreviation for the American Society of Heating, Refrigeration, and Air-Conditioning Engineers.

ASTM - Abbreviation for the American Society for Testing and Materials, which is responsible for the issue of many standard methods used in the energy industry.
**Atmospheric Pressure** - The pressure of the air at sea level; one standard atmosphere at zero degrees centigrade is equal to 14.695 pounds per square inch (1.033 kilograms per square centimeter).

**Atrium** - An interior court to which rooms open.

**Attic** - The usually unfinished space above a ceiling and below a roof.

**Attic Fan** - A fan mounted on an attic wall used to exhaust warm attic air to the outside.

**Attic Vent** - A passive or mechanical device used to ventilate an attic space, primarily to reduce heat buildup and moisture condensation.

**Automatic Damper** - A device that cuts off the flow of hot or cold air to or from a room as controlled by a thermostat.

**Average Wind Speed (or Velocity)** - The mean wind speed over a specified period of time.

**Azimuth (Solar)** - The angle between true south and the point on the horizon directly below the sun.

**Awning** - An architectural element for shading windows and wall surfaces placed on the exterior of a building; can be fixed or movable.

**Basement** - The conditioned or unconditioned space below the main living area or primary floor of a building.

**Battery** - An energy storage device composed of one or more electrolyte cells.

**Bin Method** - A method of predicting heating and/or cooling loads using instantaneous load calculation at different outdoor dry-bulb temperatures, and multiplying the result by the number of hours of occurrence of each temperature.

**Blower** - The device in an air conditioner that distributes the filtered air from the return duct over the cooling coil/heat exchanger. This circulated air is cooled/heated and then sent through the supply duct, past dampers, and through supply diffusers to the living/working space.

**Boiler** - A vessel or tank where heat produced from the combustion of fuels such as natural gas, fuel oil, or coal is used to generate hot water or steam for applications ranging from building space heating to electric power production or industrial process heat.

**British Thermal Unit (Btu)** - The amount of heat required to raise the temperature of one pound of water one degree Fahrenheit; equal to 252 calories.

**Building Envelope** - The structural elements (walls, roof, floor, foundation) of a building that encloses conditioned space; the building shell.

**Building Orientation** - The relationship of a building to true south, as specified by the direction of its longest axis.

**Bulk Density** - The weight of a material per unit of volume compared to the weight of the same volume of water.

**Capacity** - The load that a power generation unit or other electrical apparatus or heating unit is rated by the manufacture to be able to meet or supply.

**Capital Costs** - The amount of money needed to purchase equipment, buildings, tools, and other manufactured goods that can be used in production.

**Cathedral Ceiling/Roof** - A type of ceiling and roof assembly that has no attic.

**Ceiling** - The downward facing structural element that is directly opposite the floor.

**Ceiling Fan** - A mechanical device used for air circulation and to provide cooling.

**Chiller** - A device for removing heat from a gas or liquid stream for air conditioning/cooling.
Chimney - A masonry or metal stack that creates a draft to bring air to a fire and to carry the gaseous byproducts of combustion safely away.

Clerestory - A window located high in a wall near the eaves that allows daylight into a building interior, and may be used for ventilation and solar heat gain.

Climate - The prevailing or average weather conditions of a geographic region.

Codes - Legal documents that regulate construction to protect the health, safety, and welfare of people. Codes establish minimum standards but do not guarantee efficiency or quality.

Coefficient of Heat Transmission (U-Value) - A value that describes the ability of a material to conduct heat. The number of Btu that flow through 1 square foot of material, in one hour. It is the reciprocal of the R-Value (U-Value = 1/R-Value).

Coefficient of Performance (COP) - A ratio of the work or useful energy output of a system versus the amount of work or energy inputted into the system as determined by using the same energy equivalents for energy in and out. Is used as a measure of the steady state performance or energy efficiency of heating, cooling, and refrigeration appliances. The COP is equal to the Energy Efficiency Ratio (EER) divided by 3.412. The higher the COP, the more efficient the device.

Cogeneration - The generation of electricity or shaft power by an energy conversion system and the concurrent use of rejected thermal energy from the conversion system as an auxiliary energy source.

Cold Night Sky - The low effective temperature of the sky on a clear night.

Combustion - The process of burning; the oxidation of a material by applying heat, which unites oxygen with a material or fuel.

Commercial Building - A building with more than 50 percent of its floor space used for commercial activities, which include stores, offices, schools, churches, libraries, museums, health care facilities, warehouses, and government buildings except those on military bases.

Comfort Zone - A frequently used room or area that is maintained at a more comfortable level than the rest of the house; also known as a "warm room."

Conditioned Space - The interior space of a building that is heated or cooled.

Conduction - The transfer of heat through a material by the transfer of kinetic energy from particle to particle; the flow of heat between two materials of different temperatures that are in direct physical contact.

Conductivity (Thermal) - This is a positive constant, k, that is a property of a substance and is used in the calculation of heat transfer rates for materials. It is the amount of heat that flows through a specified area and thickness of a material over a specified period of time when there is a temperature difference of one degree between the surfaces of the material.

Conservation - To reduce or avoid the consumption of a resource or commodity.

Convection - The transfer of heat by means of air currents.

Conventional Heat Pump - This type of heat pump is known as an air-to-air system.

Cooling Capacity - The quantity of heat that a cooling appliance is capable of removing from a room in one hour.

Cooling Degree Day - A value used to estimate interior air cooling requirements (load) calculated as the number of degrees per day (over a specified period) that the daily average temperature is above 65 degrees Fahrenheit (or some other, specified base temperature). The daily average temperature is the mean of the maximum and minimum temperatures recorded for a specific location for a 24 hour period.

Cooling Load - That amount of cooling energy to be supplied (or heat and humidity removed) based on the sensible and latent loads.
Cooling Tower - A structure used to cool power plant water; water is pumped to the top of the tubular tower and sprayed out into the center, and is cooled by evaporation as it falls, and then is either recycled within the plant or is discharged.

Crawlspace - The unoccupied, and usually unfinished and unconditioned space between the floor, foundation walls, and the slab or ground of a building.

Damper - A movable plate used to control air flow; in a wood stove or fireplace, used to control the amount and direction of air going to the fire.

Daylighting - The use of direct, diffuse, or reflected sunlight to provide supplemental lighting for building interiors.

Declination - The angular position of the sun at solar noon with respect to the plane of the equator.

Degree Day - A unit for measuring the extent that the outdoor daily average temperature (the mean of the maximum and minimum daily dry-bulb temperatures) falls below (in the case of heating, see Heating Degree Day), or falls above (in the case of cooling, see Cooling Degree Day) an assumed base temperature, normally taken as 65 degrees Fahrenheit, unless otherwise stated. One degree day is counted for each degree below (for heating) or above (in the case of cooling) the base, for each calendar day on which the temperature goes below or above the base.

Degree Hour - The product of 1 hour, and usually the number of degrees Fahrenheit the hourly mean temperature is above a base point (usually 65 degrees Fahrenheit); used in roughly estimating or measuring the cooling load in cases where processes heat, heat from building occupants, and humidity are relatively unimportant compared to the dry-bulb temperature.

Dehumidifier - A device that cools air by removing moisture from it.

Desiccant - A material used to desiccate (dry) or dehumidify air.

Desiccant Cooling - To condition/cool air by dessication.

Desiccation - The process of removing moisture; involves evaporation.

Design Cooling Load - The amount of conditioned air to be supplied by a cooling system; usually the maximum amount to be delivered based on a specified number of cooling degree days or design temperature.

Design Heating Load - The amount of heated air, or heating capacity, to be supplied by a heating system; usually the maximum amount to be delivered based on a specified number of heating degree days or design outside temperature.

Design Temperature - The temperature that a system is designed to maintain (inside) or operate against (outside) under the most extreme conditions.

Dewpoint - The temperature to which air must be cooled, at constant pressure and water vapor content, in order for saturation or condensation to occur; the temperature at which the saturation pressure is the same as the existing vapor pressure; also called saturation point.

Diffuse Solar Radiation - Sunlight scattered by atmospheric particles and gases so that it arrives at the earth's surface from all directions and can not be focused.

DOE-2.1 - A computer software program that simulates energy consumption of commercial buildings; used for design and auditing purposes.

Domestic Hot Water - Water heated for residential washing, bathing, etc.

Double-Pane or Glazed Window - A type of window having two layers (panes or glazing) of glass separated by an air space. Each layer of glass and surrounding air space reradiates and traps some of the heat that passes through thereby increasing the windows resistance to heat loss (R-value).

Dry Bulb Temperature - The temperature of the air as measured by a standard thermometer.
Duct(s) - The round or rectangular tube(s), generally constructed of sheet metal, fiberglass board, or a flexible plastic-and-wire composite, located within a wall, floor, and ceiling that distributes heated or cooled air in buildings.

Duct Fan - An axial flow fan mounted in a section of duct to move conditioned air.

Earth Berm - A mound of dirt next to exterior walls to provide wind protection and insulation.

Earth-Coupled Ground Source (Geothermal) Heat Pump - A type of heat pump that uses sealed horizontal or vertical pipes, buried in the ground, as heat exchangers through which a fluid is circulated to transfer heat.

Efficiency - Under the First Law of Thermodynamics, efficiency is the ratio of work or energy output to work or energy input, and cannot exceed 100 percent. Efficiency under the Second Law of Thermodynamics is determined by the ratio of the theoretical minimum energy that is required to accomplish a task relative to the energy actually consumed to accomplish the task. Generally, the measured efficiency of a device, as defined by the First Law, will be higher than that defined by the Second Law.

Electric Energy - The amount of work accomplished by electrical power, usually measured in kilowatt-hours (kWh). One kWh is 1,000 Watts and is equal to 3,413 Btu.

Emissivity - The ratio of the radiant energy (heat) leaving (being emitted by) a surface to that of a black body at the same temperature and with the same area; expressed as a number between 0 and 1.

Enclosure - The housing around a motor that supports the active parts and protects them. They come in different varieties (open, protected) depending on the degree of protection required.

Energy - The capability of doing work; different forms of energy can be converted to other forms, but the total amount of energy remains the same.

Enthalpy - A thermodynamic property of a substance, defined as the sum of its internal energy plus the pressure of the substance times its volume, divided by the mechanical equivalent of heat. The total heat content of air; the sum of the enthalpies of dry air and water vapor, per unit weight of dry air; measured in Btu per pound (or calories per kilogram).

Entropy - A measure of the unavailable or unusable energy in a system; energy that cannot be converted to another form.

Environment - All the natural and living things around us. The earth, air, weather, plants, and animals all make up our environment.

Equinox - The two times of the year when the sun crosses the equator and night and day are of equal length; usually occurs on March 21st (spring equinox) and September 23 (fall equinox).

Evaporation - The conversion of a liquid to a vapor (gas), usually by means of heat.

Evaporative Cooling - The physical process by which a liquid or solid is transformed into the gaseous state. For this process a mechanical device uses the outside air's heat to evaporate water that is held by pads inside the cooler. The heat is drawn out of the air through this process and the cooled air is blown into the home by the cooler's fan.

Fan - A device that moves and/or circulates air and provides ventilation for a room or a building.

Federal Energy Management Program (FEMP) - A program of the U.S. Department of Energy (DOE) that implements energy legislation and presidential directives. FEMP provides project financing, technical guidance and assistance, coordination and reporting, and new initiatives for the federal government. It also helps federal agencies identify the best technologies and technology demonstrations for their use.
First Law of Thermodynamics - States that energy cannot be created or destroyed, but only changed from one form to another. First Law efficiency measures the fraction of energy supplied to a device or process that it delivers in its output. Also called the law of conservation of energy.

Flat Roof - A slightly sloped roof, usually with a tar and gravel cover. Most commercial buildings use this kind of roof.

Floor - The upward facing structure of a building.

Forced Ventilation - A type of building ventilation system that uses fans or blowers to provide fresh air to rooms when the forces of air pressure and gravity are not enough to circulate air through a building.

Foundation - The supportive structure of a building.

Fuel Cell - An electrochemical device that converts chemical energy directly into electricity.

Geothermal Energy - Energy produced by the internal heat of the earth; geothermal heat sources include: hydrothermal convective systems; pressurized water reservoirs; hot dry rocks; manual gradients; and magma. Geothermal energy can be used directly for heating or to produce electric power.

Geothermal Heat Pump - A type of heat pump that uses the ground, ground water, or ponds as a heat source and heat sink, rather than outside air. Ground or water temperatures are more constant and are warmer in winter and cooler in summer than air temperatures. Geothermal heat pumps operate more efficiently than "conventional" or "air source" heat pumps.

Gigawatt (GW) - A unit of power equal to 1 billion Watts; 1 million kilowatts, or 1,000 megawatts.

Glazing - A term used for the transparent or translucent material in a window. This material (i.e. glass, plastic films, coated glass) is used for admitting solar energy and light through windows.

Greywater - Waste water from a household source other than a toilet. This water can be used for landscape irrigation depending upon the source of the greywater.

Ground-Source Heat Pump (see geothermal systems)

Heat - A form of thermal energy resulting from combustion, chemical reaction, friction, or movement of electricity. As a thermodynamic condition, heat, at a constant pressure, is equal to internal or intrinsic energy plus pressure times volume.

Heat Exchanger - A device used to transfer heat from a fluid (liquid or gas) to another fluid where the two fluids are physically separated.

Heat Gain - The amount of heat introduced to a space from all heat producing sources, such as building occupants, lights, appliances, and from the environment, mainly solar energy.

Heating Degree Day(s) (HDD) - The number of degrees per day that the daily average temperature (the mean of the maximum and minimum recorded temperatures) is below a base temperature, usually 65 degrees Fahrenheit, unless otherwise specified; used to determine indoor space heating requirements and heating system sizing. Total HDD is the cumulative total for the year/heating season. The higher the HDD for a location, the colder the daily average temperature(s).

Heating Load - The rate of heat flow required to maintain a specific indoor temperature; usually measured in Btu per hour.
Heating Seasonal Performance Factor (HSPF) - The measure of seasonal or annual efficiency of a heat pump operating in the heating mode. It takes into account the variations in temperature that can occur within a season and is the average number of Btu of heat delivered for every watt-hour of electricity used by the heat pump over a heating season.

Heating, Ventilation, and Air-Conditioning (HVAC) System - All the components of the appliance used to condition interior air of a building.

Heat Pump - An electricity powered device that extracts available heat from one area (the heat source) and transfers it to another (the heat sink) to either heat or cool an interior space or to extract heat energy from a fluid.

Heat Transfer - The flow of heat from one area to another by conduction, convection, and/or radiation. Heat flows naturally from a warmer to a cooler material or space.

Humidity - A measure of the moisture content of air; may be expressed as absolute, mixing ratio, saturation deficit, relative, or specific.

Hydronic Heating Systems - A type of heating system where water is heated in a boiler and either moves by natural convection or is pumped to heat exchangers or radiators in rooms; radiant floor systems have a grid of tubing laid out in the floor for distributing heat. The temperature in each room is controlled by regulating the flow of hot water through the radiators or tubing.

*1*

Incident Solar Radiation - The amount of solar radiation striking a surface per unit of time and area.

Indirect Solar Gain System - A passive solar heating system in which the sun warms a heat storage element, and the heat is distributed to the interior space by convection, conduction, and radiation.

Induction Motor - A motor in which a three phase (or any multiphase) alternating current (i.e. the working current) is supplied

Insolation - The solar power density incident on a surface of stated area and orientation, usually expressed as Watts per square meter or Btu per square foot per hour.

Insulation - Materials that prevent or slow down the movement of heat.

*J*

Joule - A metric unit of energy or work; the energy produced by a force of one Newton operating through a distance of one meter; 1 Joule per second equals 1 Watt or 0.737 foot-pounds; 1 Btu equals 1,055 Joules.

*K*

Kilowatt (kW) - A standard unit of electrical power equal to one thousand watts, or to the energy consumption at a rate of 1000 Joules per second.

Kilowatt-hour - A unit or measure of electricity supply or consumption of 1,000 Watts over the period of one hour; equivalent to 3,412 Btu.

*L*

Landscaping - Features and vegetation on the outside of or surrounding a building for aesthetics and energy conservation.

Latent Cooling Load - The load created by moisture in the air, including from outside air infiltration and that from indoor sources such as occupants, plants, cooking, showering, etc.

Latent Heat - The change in heat content that occurs with a change in phase and without change in temperature.

Latent Heat of Vaporization - The quantity of heat produced to change a unit weight of a liquid to vapor with no change in temperature.
Load - The demand on an energy producing system; the energy consumption or requirement of a piece or group of equipment.

Local Solar Time - A system of astronomical time in which the sun crosses the true north-south meridian at 12 noon, and which differs from local time according to longitude, time zone, and equation of time.

Losses (Energy) - A general term applied to the energy that is converted to a form that can not be effectively used (lost) during the operation of an energy producing, conducting, or consuming system.

Low-E Coatings & (Window) Films - A coating applied to the surface of the glazing of a window to reduce heat transfer through the window.

*M*

Make-Up Air - Air brought into a building from outside to replace exhaust air.

Manual J - The standard method for calculating residential cooling loads developed by the Air-Conditioning and Refrigeration Institute (ARI) and the Air Conditioning Contractors of America (ACCA) based largely on the American Society of Heating, Refrigeration, and Air-Conditioning Engineer's (ASHRAE) "Handbook of Fundamentals."

Mean Wind Speed - The arithmetic wind speed over a specified time period and height above the ground (the majority of U.S. National Weather Service anemometers are at 20 feet (6.1 meters)).

Mechanical Systems - Those elements of building used to control the interior climate.

Megawatt - One thousand kilowatts, or 1 million watts; standard measure of electric power plant generating capacity.

*N*

Natural Cooling - Space cooling achieved by shading, natural (unassisted, as opposed to forced) ventilation, conduction control, radiation, and evaporation; also called passive cooling.

Natural Draft - Draft that is caused by temperature differences in the air.

Natural Ventilation - Ventilation that is created by the differences in the distribution of air pressures around a building. Air moves from areas of high pressure to areas of low pressure with gravity and wind pressure affecting the airflow. The placement and control of doors and windows alters natural ventilation patterns.

Nocturnal Cooling - The effect of cooling by the radiation of heat from a building to the night sky.

*O*

Occupancy Sensor - An optical, ultrasonic, or infrared sensor that turns room lights on when they detect a person's presence and off after the space is vacated.

Occupied Space - The space within a building or structure that is normally occupied by people, and that may be conditioned (heated, cooled and/or ventilated).

Off-Peak - The period of low energy demand, as opposed to maximum, or peak, demand.

On-Site Generation - Generation of energy at the location where all or most of it will be used.

Orientation - The alignment of a building along a given axis to face a specific geographical direction. The alignment of a solar collector, in number of degrees east or west of true south.

Overhang - A building element that shades windows, walls, and doors from direct solar radiation and protects these elements from precipitation.

*P*

Pane (Window) - The area of glass that fits in the window frame.

Passive/Natural Cooling - To allow or augment the natural movement of cooler air from exterior, shaded areas of a building through or around a building.
**Passive Solar (Building) Design** - A building design that uses structural elements of a building to heat and cool a building, without the use of mechanical equipment, which requires careful consideration of the local climate and solar energy resource, building orientation, and landscape features, to name a few. The principal elements include proper building orientation, proper window sizing and placement and design of window overhangs to reduce summer heat gain and ensure winter heat gain, and proper sizing of thermal energy storage mass (for example a Trombe wall or masonry tiles). The heat is distributed primarily by natural convection and radiation, though fans can also be used to circulate room air or ensure proper ventilation.

**Payback** - The amount of time required for positive cash flows to equal the total investment costs.

**Plenum** - The space between a hanging ceiling and the floor above or roof; usually contains HVAC ducts, electrical wiring, fire suppression system piping, etc.

**Power** - Energy that is capable or available for doing work; the time rate at which work is performed, measured in horsepower, Watts, or Btu per hour. Electric power is the product of electric current and electromotive force.

**Pressure Drop** - The loss in static pressure of a fluid (liquid or gas) in a system due to friction from obstructions in pipes, from valves, fittings, regulators, burners, etc, or by a breech or rupture of the system. **Pressurization Testing** - A technique used by energy auditors, using a blower door, to locate areas of air infiltration by exaggerating the defects in the building shell. This test only measures air infiltration at the time of the test. It does not take into account changes in atmospheric pressure, weather, wind velocity, or any activities the occupants conduct that may affect air infiltration rates over a period of time.

**Psi** - Pounds of pressure per square inch.

**Psychometric** - An instrument for measuring relative humidity by means of wet and dry-bulb temperatures.

**Q**

**R**

**Radiant Floor** - A type of radiant heating system where the building floor contains channels or tubes through which hot fluids such as air or water are circulated. The whole floor is evenly heated. Thus, the room heats from the bottom up. Radiant floor heating eliminates the draft and dust problems associated with forced air heating systems.

**Radiant Heating System** - A heating system where heat is supplied (radiated) into a room by means of heated surfaces, such as electric resistance elements, hot water (hydronic) radiators, etc.

**Radiation** - The transfer of heat through matter or space by means of electromagnetic waves.

**Reflectance** - The amount (percent) of light that is reflected by a surface relative to the amount that strikes it.

**Relative Humidity** - A measure of the percent of moisture actually in the air compared with what would be in it if it were fully saturated at that temperature. When the air is fully saturated, its relative humidity is 100 percent.

**Renewable Energy** - Energy derived from resources that are regenerative or for all practical purposes can not be depleted. Types of renewable energy resources include moving water (hydro, tidal and wave power), thermal gradients in ocean water, biomass, geothermal energy, solar energy, and wind energy. Municipal solid waste (MSW) is also considered to be a renewable energy resource.

**Resistance** - The inherent characteristic of a material to inhibit the transfer of energy. In electrical conductors, electrical resistance results in the generation of heat. Electrical resistance is measured in Ohms. The heat transfer resistance properties of insulation products are quantified as the R-value.

**Restructuring** - The process of changing the structure of the electric power industry from one of guaranteed monopoly over service territories, as established by the Public Utility Holding Company Act of 1935, to one of open competition between power suppliers for customers in any area.
Retrofit - The process of modifying a building's structure.

Return Air - Air that is returned to a heating or cooling appliance from a heated or cooled space.

Return Duct - The central heating or cooling system contains a fan that gets its air supply through these ducts, which ideally should be installed in every room of the house. The air from a room will move towards the lower pressure of the return duct.

Roof - A building element that provides protection against the sun, wind, and precipitation.

R-Value - A measure of the capacity of a material to resist heat transfer. The R-Value is the reciprocal of the conductivity of a material (U-Value). The larger the R-Value of a material, the greater its insulating properties.

*S*

Seasonal Energy Efficiency Ratio (SEER) - A measure of seasonal or annual efficiency of a central air conditioner or air conditioning heat pump. It takes into account the variations in temperature that can occur within a season and is the average number of Btu of cooling delivered for every watt-hour of electricity used by the heat pump over a cooling season. It represents the total seasonal cooling output in Btu divided by the total seasonal electric input in watt-hours (Wh). Thus, the resultant value for SEER has units of Btu/Wh.

Second Law of Thermodynamics - This law states that no device can completely and continuously transform all of the energy supplied to it into useful energy.

Sensible Cooling Load - The interior heat gain due to heat conduction, convection, and radiation from the exterior into the interior, and from occupants and appliances.

Setback Thermostat - A thermostat that can be set to automatically lower temperatures in an unoccupied house and raise them again before the occupant returns.

Shading Coefficient - A measure of window glazing performance that is the ratio of the total solar heat gain through a specific window to the total solar heat gain through a single sheet of double-strength glass under the same set of conditions; expressed as a number between 0 and 1.

Single Glaze or Pane - One layer of glass in a window frame. It has very little insulating value (R-1) and provides only a thin barrier to the outside and can account for considerable heat loss and gain.

Skylight - A window located on the roof of a structure to provide interior building spaces with natural daylight, warmth, and ventilation.

Slab - A concrete pad that sits on gravel or crushed rock, well-compacted soil either level with the ground or above the ground.

Solar Altitude Angle - The angle between a line from a point on the earth's surface to the center of the solar disc, and a line extending horizontally from the point.

Solar Azimuth - The angle between the sun's apparent position in the sky and true south, as measured on a horizontal plane.

Solar Declination - The apparent angle of the sun north or south of the earth's equatorial plane. The earth's rotation on its axis causes a daily change in the declination.

Solar Energy - Electromagnetic energy transmitted from the sun (solar radiation). The amount that reaches the earth is equal to one billionth of total solar energy generated, or the equivalent of about 420 trillion kilowatt-hours.

Solar Gain - The amount of energy that a building absorbs due to solar energy striking its exterior and conducting to the interior or passing through windows and being absorbed by materials in the building.

Solar Heat Gain Coefficient (SHGC) - The ratio of the total solar heat admittance of a given window product relative to the solar heat incident on the projected window surface at normal solar incidence (i.e. perpendicular to the glazing surface).
**Solar Irradiation** - The amount of solar radiation, both direct and diffuse, received at any location.

**Solar Mass** - A term used for materials used to absorb and store solar energy.

**Solar Radiation** - A general term for the visible and near visible (ultraviolet and near-infrared) electromagnetic radiation that is emitted by the sun. It has a spectral, or wavelength, distribution that corresponds to different energy levels; short wavelength radiation has a higher energy than long-wavelength radiation.

**Solar Time** - The period marked by successive crossing of the earth's meridian by the sun; the hour angle of the sun at a point of observance (apparent time) is corrected to true (solar) time by taking into account the variation in the earth's orbit and rate of rotation. Solar time and local standard time are usually different for any specific location.

**Solstice** - The two times of the year when the sun is apparently farthest north and south of the earth's equator; usually occurring on or around June 21 (summer solstice in northern hemisphere, winter solstice for southern hemisphere) and December 21 (winter solstice in northern hemisphere, summer solstice for the southern hemisphere).

**Specific Heat** - The amount of heat required to raise a unit mass of a substance through one degree, expressed as a ratio of the amount of heat required to raise an equal mass of water through the same range.

**Specific Heat Capacity** - The quantity of heat required to change the temperature of one unit weight of a material by one degree.

**Specific Humidity** - The weight of water vapor, per unit weight of dry air.

**Specific Volume** - The volume of a unit weight of a substance at a specific temperature and pressure.

**Stack** - A smokestack or flue for exhausting the products of combustion from a combustion appliance.

**Standard Air** - Air with a weight of 0.075 pounds per cubic foot with an equivalent density of dry air at a temperature of 86 degrees Fahrenheit and standard barometric pressure of 29.92 inches of mercury.

**Standard Conditions** - In refrigeration, an evaporating temperature of 5 degrees Fahrenheit (F), a condensing temperature of 86 degrees F., liquid temperature before expansion of 77 degrees F., and suction temperature of 12 degrees F.

**Standard Cubic Foot** - A column of gas at standard conditions of temperature and pressure (32 degrees Fahrenheit and one atmosphere).

**Steam** - Water in vapor form; used as the working fluid in steam turbines and heating systems.

**Sun Path Diagram** - A circular projection of the sky vault onto a flat diagram used to determine solar positions and shading effects of landscape features on a solar energy system.

**Supply Duct** - The duct(s) of a forced air heating/cooling system through which heated or cooled air is supplied to rooms by the action of the fan of the central heating or cooling unit.

**Swamp Cooler** - A popular term used for an evaporative cooling device.

**T**

**Temperature Zones** - Individual rooms or zones in a building where temperature is controlled separately from other rooms or zones.

**Therm** - A unit of heat containing 100,000 British thermal units (Btu).

**Thermal Energy Storage** - The storage of heat energy during utility off-peak times at night, for use during the next day without incurring daytime peak electric rates.

**Thermal Mass** - Materials that store heat.

**Thermal Resistance (R-Value)** - This designates the resistance of a material to heat conduction. The greater the R-value the larger the number.
Thermostat - A device used to control temperatures; used to control the operation of heating and cooling devices by turning the device on or off when a specified temperature is reached.

Ton (of Air Conditioning) - A unit of air cooling capacity; 12,000 Btu per hour.

Triple Pane (Window) - This represents three layers of glazing in a window with an airspace between the middle glass and the exterior and interior panes.

Trombe Wall - A wall with high thermal mass used to store solar energy passively in a solar home. The wall absorbs solar energy and transfers it to the space behind the wall by means of radiation and by convection currents moving through spaces under, in front of, and on top of the wall.

*U*

U-Value (see Coefficient of Heat Transmission) - The reciprocal of R-Value. The lower the number, the greater the heat transfer resistance (insulating) characteristics of the material. The units of U-value are Btu/hr-ft²-oF.

*V*

Vent - A component of a heating or ventilation appliance used to conduct fresh air into, or waste air or combustion gases out of, an appliance or interior space.

Ventilation - The process of moving air (changing) into and out of an interior space either by natural or mechanically induced (forced) means.

*W*

Wall - A vertical structural element that holds up a roof, encloses part or all of a room, or stands by itself to hold back soil.

Wall Orientation - The geographical direction that the primary or largest exterior wall of a building faces.

Water Source Heat Pump - A type of (geothermal) heat pump that uses well (ground) or surface water as a heat source. Water has a more stable seasonal temperature than air thus making for a more efficient heat source.

Watt - The rate of energy transfer equivalent to one ampere under an electrical pressure of one volt. One watt is equal to 3.413 Btu/h. One watt equals 1/746 horsepower, or one joule per second. It is the product of Voltage and Current (amperage). The term 'kW' stands for "kilowatt" or 1,000 watts. The term 'MW' stands for "Megawatt" or 1,000,000 watts.

Watt-hour - A unit of electricity consumption of one Watt over the period of one hour.

Window - A generic term for a glazed opening that allows daylight to enter into a building and can be opened for ventilation.

Wind Rose - A diagram that indicates the average percentage of time that the wind blows from different directions, on a monthly or annual basis.

Wind Speed - The rate of flow of the wind undisturbed by obstacles.

Wind Velocity - The wind speed and direction in an undisturbed flow.

*X*

*Y*

*Z*

Zone - An area within the interior space of a building, such as an individual room(s), to be cooled, heated, or ventilated. A zone has its own thermostat to control the flow of conditioned air into the space.

Zoning - The combining of rooms in a structure according to similar heating and cooling patterns. Zoning requires using more than one thermostat to control heating, cooling, and ventilation equipment.
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