



The diagram features two identical geometric structures on a light yellow background. Each structure is composed of three overlapping circles, creating a central hexagonal area and six outer points. These circles are enclosed within a larger triangular frame. A vertical dotted line bisects each structure. Two diagonal dotted lines extend from the top corners of the triangular frames towards the right side of the page. The title 'NATURAL VENTILATION IN NORTHWEST BUILDINGS' is centered horizontally between the two structures.

NATURAL VENTILATION IN NORTHWEST BUILDINGS

NATURAL VENTILATION IN NORTHWEST BUILDINGS

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*June, 2004
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ISBN 0-87114-356-9

*Prepared for
The BetterBricks program of the Northwest Energy Efficiency Alliance
Seattle City Light*

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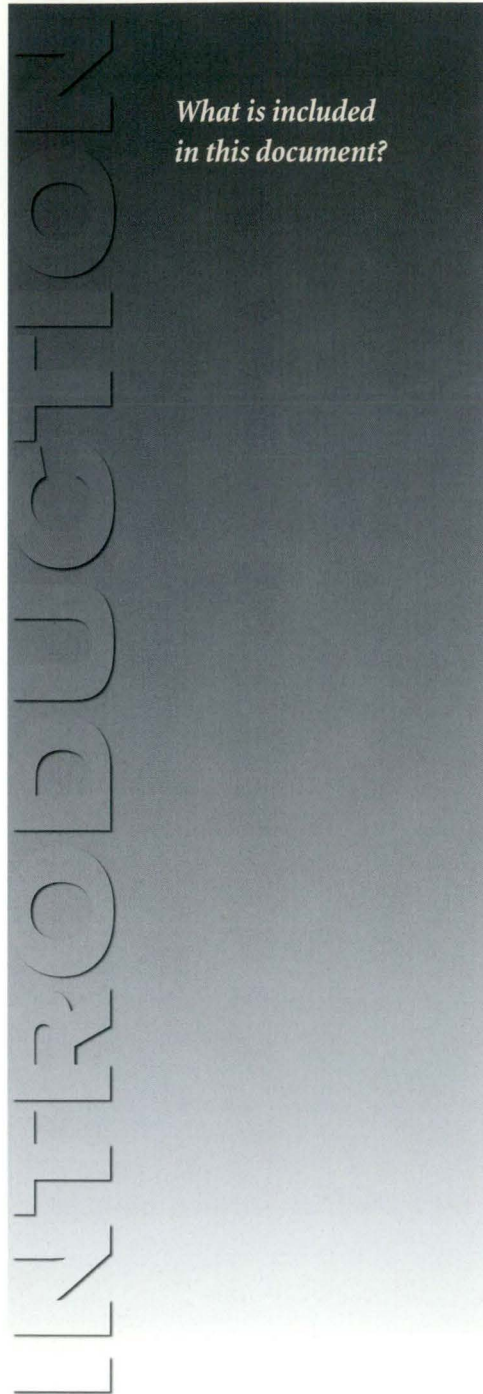
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What is included
in this document?

INTRODUCTION

This document's primary text is a series of questions and answers on the left side of the page. This text is augmented by examples and sidebars on the right-hand side. The text is divided into five sections.



The **VENTING** section introduces basic concepts and explains how cross and stack ventilation function. It addresses questions such as: What is natural ventilation? Why should buildings be naturally ventilated? p.6



The **BENEFITS** section highlights some of the advantages of natural ventilation and addresses questions such as: Can the size and first cost of the mechanical system be reduced by using natural ventilation? Are people more or less productive in naturally ventilated buildings? p. 12



The **FEASIBILITY** section discusses when and where natural ventilation can be effectively used in the Northwest and answers questions such as: How can cool night temperatures be used to offset hot day temperatures? How does a building's occupant use schedule affect the feasibility of natural ventilation cooling? p. 16



The **TOOLS** section covers analysis, design, and evaluation. Questions in this section include: What site organization strategies place buildings to maximize their potential for ventilation? What strategies are available to augment natural ventilation with mechanical ventilation? p. 26



The **BARRIERS** section outlines some circumstances that make natural ventilation difficult to use and addresses questions such as: Aren't naturally ventilated buildings more expensive? Won't undesirable outside conditions like high temperature, pollen-laden air, or noise reduce the productivity of building occupants? p. 46

Questions About
Natural Ventilation

Sections
Color Coded



Answers to Natural
Ventilation Questions

Examples of Naturally Ventilated Buildings:
Mithun Offices (p. 7), Hood River Library (p. 13),
IslandWood School (p. 33), and Lillis Business Center (p. 47)



Graphs and Illustrations:
Ventilation Rates (p. 11), Productivity (p. 15), Daytime
Ventilation Feasibility (p. 21), Nighttime Ventilation of Mass
Feasibility (p. 25), Stack and Cross Ventilation (p. 37)

Conceptual and In-Depth
Explanations of Natural
Ventilation Phenomena

What is natural ventilation?

Why should buildings be naturally ventilated?

When should a building not be naturally ventilated?

VENTING

- Natural ventilation is the use of a building's form, organization, and openings in conjunction with naturally occurring phenomena such as the wind or warm air buoyancy to supply air to its occupants and to remove heat both from the occupants and the building.

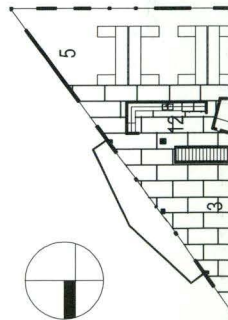
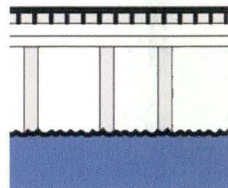


- To reduce operating costs by decreasing or eliminating the power used to mechanically ventilate and cool.
- To reduce construction costs by downsizing or eliminating the cooling equipment.
- To reduce building energy use and thereby also reduce the environmental impact caused by power generation.
- To potentially increase the productivity of building occupants due to real or perceived improvements in the indoor environment.



- When complete mechanical, heating, cooling, and ventilation systems are required for an entire building so that natural ventilation is redundant and may not be cost effective.
- When critical pressurization differences are required between spaces to maintain high levels of air quality for special uses, such as laboratories.
- When the early and continuous owner-architect-engineer collaboration that is necessary to achieve an integrated design is not feasible (Grumann, p.27).
- When outside conditions such as poor air quality, noise, or the need for security limit the time periods it is useful.

CASE STUDY



Drawings are by Mithun, Inc.
Photographs are by Robert Pisano

MITHUN OFFICES PIER 56

		Air is moved by:		
		Cross	Stack	Fan
Ventilation is used for:	Outside Air			
	Cool People			
	Cool Space			
	Cool Mass			

The Mithun Offices project is a renovation of the 36,000 sf historic Pier 56 on Seattle's urban waterfront.

The matrix above gives a synopsis of the ventilation features. The columns indicate the predominant mode of air movement, while the rows show what the ventilation is used for.

In the Mithun offices, cross and stack ventilation are used to supply outside air, varied people cooling, and modest space cooling. In addition to ventilation through the windows, there is an air distribution system for the offices that includes fan-assisted air movement to provide ducted minimum ventilation.

Location: Seattle, Washington

Owner: Mithun Architects + Designers + Planners

Architect: Mithun Architects + Designers + Planners

Mechanical Design/Build Contractor: Holladay Parks

Natural Ventilation Consulting Engineer: Keen Engineering

Monitor windows are outlets for cross and stack ventilation

Operable windows are inlets for cross and stack ventilation; these cool people as well as remove heat

Office Space

Tenant Space

Workstations organized parallel to cross vent flow maximizes potential to cool all occupants

How does natural ventilation work?

What can natural ventilation be used for?

What causes air to flow “naturally” into, through, and out of buildings by cross ventilation?

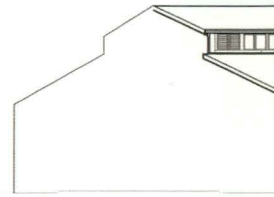
- Natural ventilation occurs when, due to pressure differences between spaces within and around buildings, air flows from one space to another. These pressure differences are caused by the forces of the wind and by gravity, which causes heavier, cooler air to drop and warmer, more buoyant air to rise. The shape and form of the building and its openings are key factors in determining the magnitude of these pressure differences.



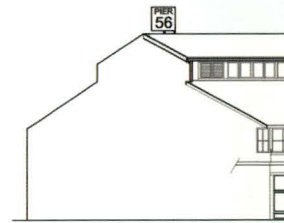
- Natural ventilation can be used to supply outside air for occupants to breathe, to reduce odors and pollutants produced from people and other internal sources, to make people feel cooler by increasing heat loss from their skin by evaporation/convection, to remove heat from the space, and (at night) to remove heat stored in the building mass so that the mass can be used to cool the space the next day.



- As a result of inertia, air tends to continue moving in the same direction when it meets a building and therefore flows around it—like water flows around a rock in a stream (rather than bouncing off it in random directions). As the wind/air flows around a building, it creates a higher pressure zone on the windward side of the building and lower pressure zones on the other sides and roof of the building.
- Because air flows from high-pressure to low-pressure zones, if openings are placed on both the windward side of the building (high pressure) and the leeward sides (low pressure) air will flow through the space that connects the two openings. Wind-driven systems are referred to as cross ventilation.
- Cross ventilation airflow through the space is dependent on opening size, wind speed and direction, building shape, and opening location.



CASE STUDY MITHUN OFFICES



Open plan allows ventilation air unobstructed through the space



Venting on Venting

Using “natural” as a term to describe some forms of ventilation puts other forms of ventilation in the category of “unnatural,” or not in accordance with nature.

This is problematic since all forms of building ventilation are governed by verifiable laws that describe the interaction of elements in the physical world. All ventilation types are similar in that they utilize pressure differences that cause air to flow from one space to another. However, the types of energy used to create pressure gradients vary.

“Mechanical” ventilation has been defined as “ventilation provided by mechanically powered equipment, such as motor-driven fans and blowers, but not by devices such as wind-driven turbine ventilators” (ASHRAE 62-2001, p.4), and therefore is dependent on manufactured energy, such as electricity.

Forms of “natural” ventilation, on the other hand, are activated by the forces of the wind or gravity.

While this paper uses the terms “mechanical” and “natural,” it is perhaps useful to think of ventilation either as dependent on manufactured energy or independent of it (i.e., powered by wind or gravity).

Manually controlled operable windows

Monitor windows are for outlets

Doors can be opened for venting

*What causes air to flow
“naturally” into, through,
and out of buildings by
stack ventilation?*

*Are natural and mechanical
ventilation systems
used together?*

- A pressure difference inside buildings also causes air flow, but in a generally vertical direction as opposed to the generally horizontal flow caused by the wind. As the air in a building is warmed by people, lights, etc., it becomes less dense and therefore lighter and has a lower pressure than the cooler, denser, heavier air outside the building.
- If openings are placed at both the top and bottom of the building, warm air will flow out the top and be replaced by cooler, heavier air flowing in at the bottom.
- These forces of wind and gravity are always acting in natural ventilation systems. However, systems that primarily rely on gravity are called stack ventilation and often have exhaust shafts, towers, or atriums to increase the distance between inlets and outlets.



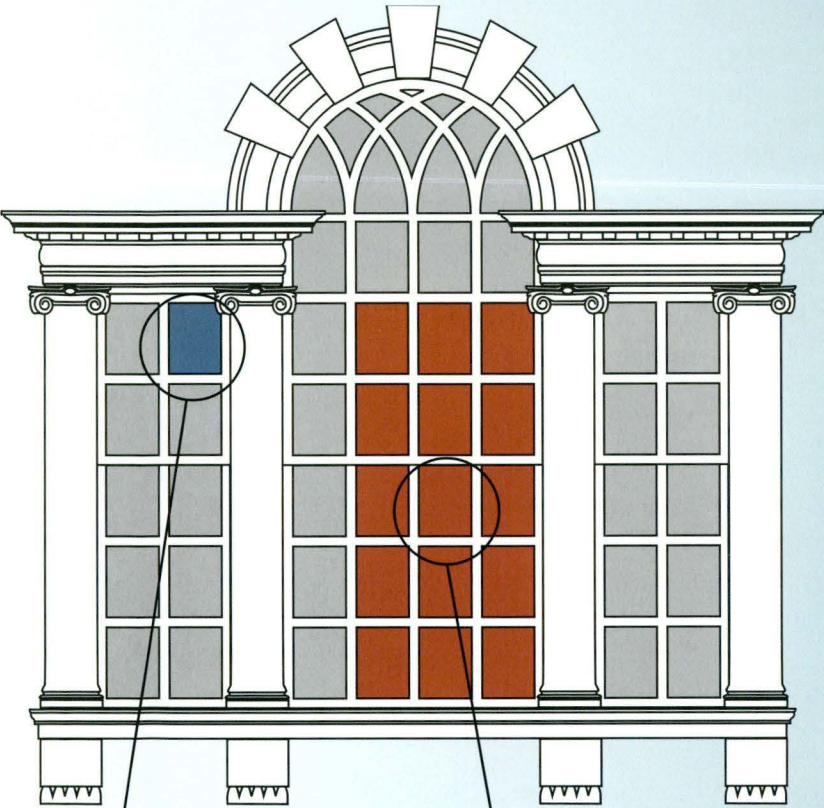
- When natural and mechanical heating, ventilation, and air conditioning systems are combined, one or the other is usually primary. This reduces duplication, which saves money and materials.
- The systems can be coordinated either by location in the building, with natural ventilation handling one part of the building and mechanical HVAC the other, or by task, for example, with natural ventilation supplying outside air for people, while cooling is provided mechanically.
- Most often, natural ventilation systems handle the average conditions while mechanical systems take care of the peak conditions.
- Natural ventilation systems can also be augmented by ceiling or other local fans which increase air movement across people making them feel cooler.

VARIATION IN

Illustration by George Wehn.
Palladian window from
Mount Pleasant, Fairmount
Park, Philadelphia, PA, 1761.

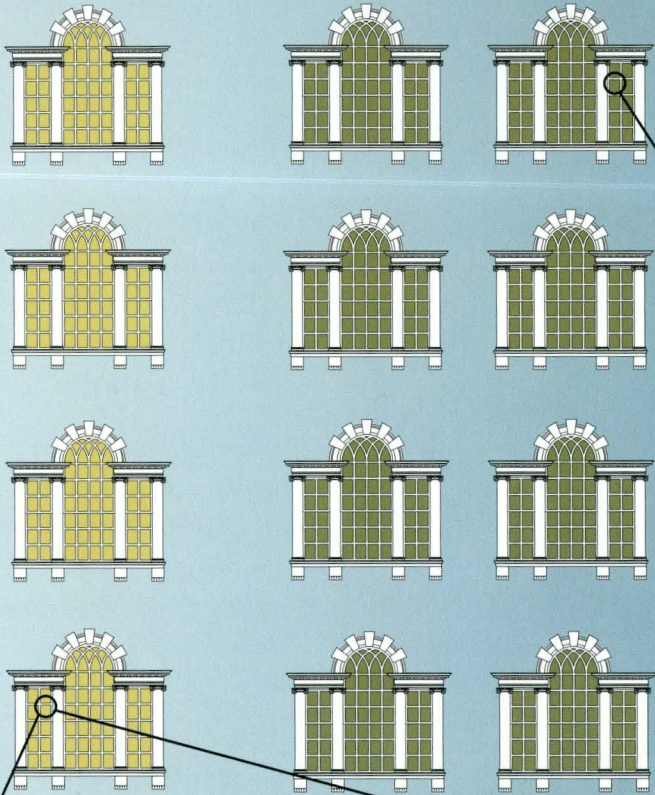
VENTILATION RATES

There are substantial differences in the amounts of air required for different types of ventilation. The opening required for night ventilation of mass is more than 40 times that required for minimum outside air (odor), and 20 times that required for space or people cooling. These rates determine the opening sizes for inlets and outlets between the interior and exterior and between spaces within the building, and also determine the sizes of ducts and fans.



The blue area represents the amount of outside air required to supply oxygen for one person; it is less than 1 cfm (ASHRAE 62-2001, p. 25).

The amount of outside air required to remove odors is 15 cfm (the basis for many minimum ventilation standards), as shown in red.



The amount of air movement needed to make a person feel 1°F cooler is approximately 30 fpm. Assuming that a person occupies a two-dimensional plane of space that is 1.5 ft x 6 ft or 9 s.f., then the air needed is approximately 300 cfm (1.5 x 6 x 30 fpm).

An office space 12 ft x 12 ft x 8 ft, with a single occupant, that gains 6 Btu/sf/hr from lights, equipment, etc. would require approximately 300 cfm to remove heat from the space and keep the inside temperature within 3° F of the ambient temperature.

To cool mass, assuming 30 air changes per hour, would require 600 cfm.

Can the utility costs of a building be reduced by the use of natural ventilation?

Can the size and first cost of the mechanical system be reduced by using natural ventilation?

B E N E F I T S

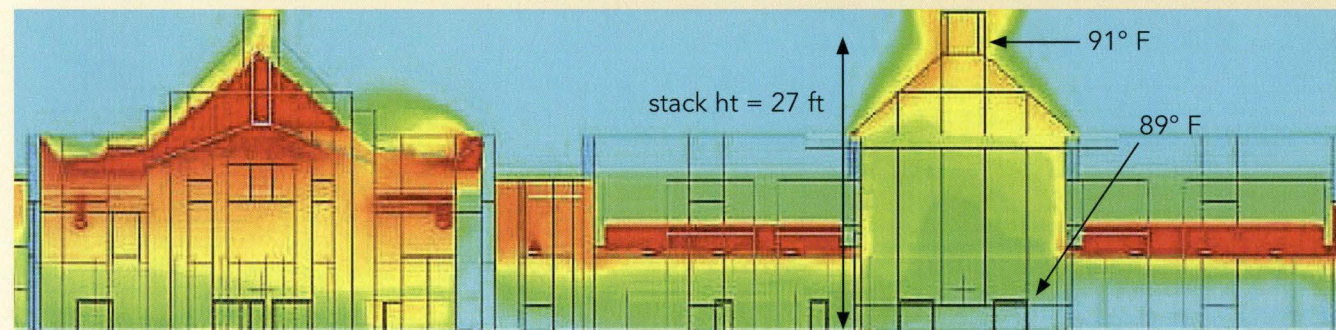
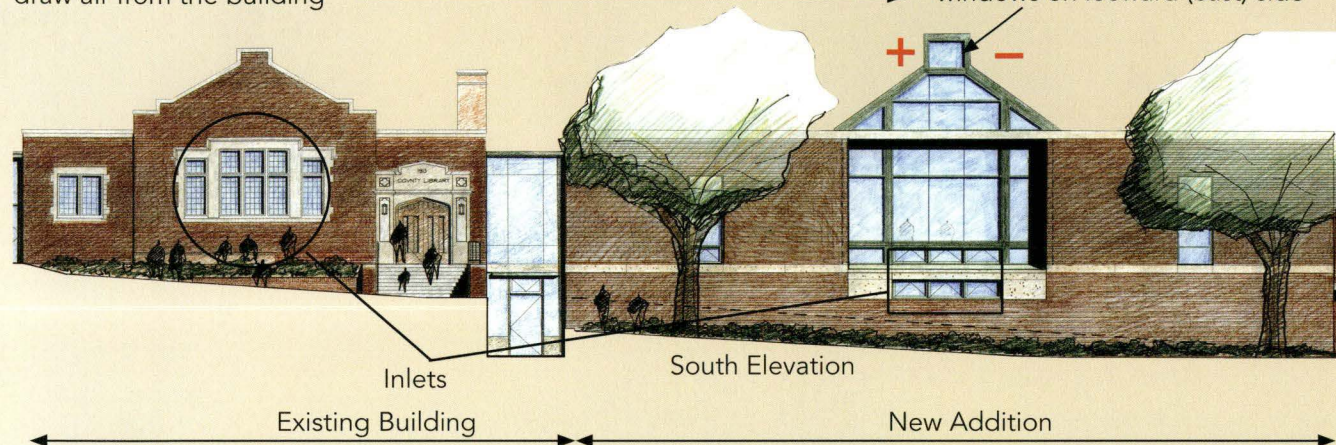
- The larger the share of the ventilation and cooling load that can be handled by natural ventilation, the greater the potential for reducing operating energy and costs. Substituting natural ventilation for mechanically supplied outside air (OSA) and cooled air reduces the number of hours per year the mechanical system must operate and therefore reduces the cost of utilities.
 - Of the total energy used for all U.S. buildings, 7% is for cooling and 3.2% is for ventilation. Cooling energy use ranges from 900 Btu/sf./yr for warehouses, to 9,100 Btu/sf./yr for office buildings, to 19,500 Btu/sf./yr for food service. Ventilation energy use for warehouses is 300 Btu/sf./yr; for offices, 5,200 Btu/sf./yr; and for health care, 7,200 Btu/sf./yr. (U.S. DOE Office of Energy Efficiency and Renewable Energy).
 - While the potential for savings is significant, if the natural ventilation system is not designed to mesh with the mechanical system, the actual cost of operating the building may increase (for example, if windows are left open when the mechanical cooling system is operating).
-
- The median first cost of heating, ventilating, and air conditioning systems in the Northwest varies from \$4.20/sf in factories to \$13.30/sf in restaurants. In Seattle and Portland the cost for offices is \$7.70/sf, and is \$10.70/sf for schools, which is approximately 12% of the construction budget (R.S. Means).
 - A reduction in first cost is possible either by downsizing or by eliminating the mechanical ventilation and cooling systems. For example, if the outside air (OSA) requirements for occupants can be met all year using natural ventilation, this frees the mechanical system from having to supply air, which requires ducts. Water

CASE STUDY

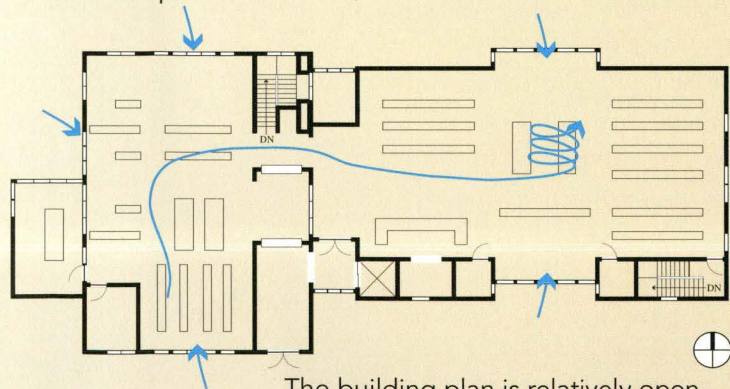
Illustrations are by Fletcher Farr Ayotte, except CFD model by Andy Solberg, IDC.

Prevailing wind direction creates low pressure area to draw air from the building

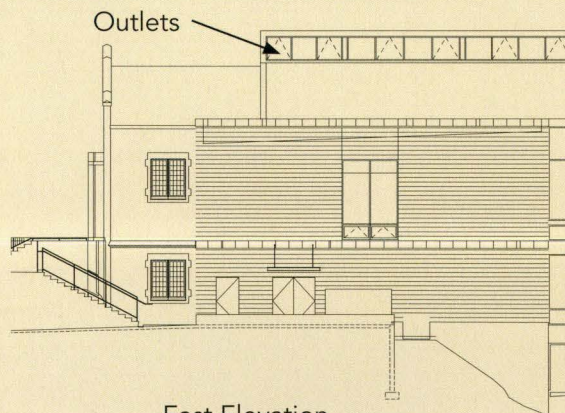
Exhaust cupola with operable windows on leeward (east) side



Computational Fluid Dynamics analysis during the design process of stack ventilation and interior temperature; outside temperature = 89° F, no wind



The building plan is relatively open and free of obstructions to air flow



East Elevation

HOOD RIVER PUBLIC LIBRARY

		Air is moved by:		
		Cross	Stack	Fan
Ventilation is used for:	Outside Air			
	Cool People			
	Cool Space			
	Cool Mass			

The Hood River Public Library utilizes a “wind tower” – a gabled roof with high openings on the leeward side – to take advantage of windy summer days. Modeling showed that on a typical hot summer day (81°F and wind 17 mph), despite internal heat gains, ventilation will keep the interior temperature of the existing building and the second floor of the new addition at or below the temperature, which 90% of people will find comfortable. A back-up HVAC system is in place for times when the natural ventilation system cannot adequately cool, estimated to be 14 days per year. When the building's windows are open the HVAC dampers are closed.

Location: Hood River, Oregon

Owner: Hood River County Library

Architect: Fletcher Farr Ayotte

Mechanical Electrical Engineers:

CBG Consulting Engineers

Natural Ventilation Consultant:

Industrial Design & Construction

Can the size and first cost of the mechanical system be reduced by using natural ventilation?

Are people more or less productive in naturally ventilated buildings?

in smaller pipes can then be used as the heat transfer medium, reducing the size and cost of the distribution system.

- Buildings that have seasonal (like schools) and daily (early shift workers) use patterns that miss peak cooling periods, are designed to have low cooling loads, and are thermally massive can substantially reduce the size or even eliminate their mechanical cooling systems.
 - Downsizing the cooling systems requires that the peak load be reduced. The cost of making the changes necessary to downsize the cooling system depends on what is already included in the design. For example, if the building or space design permits cross ventilation, there are already operable windows in the design, the construction is thermally massive, and users will open and close windows when appropriate, then night ventilation of mass is a low-cost cooling strategy. On the other hand, if none of these elements were included in the design, the increase in cost to include them would probably exceed the savings from downsizing the system.
- 
- Occupant benefits from natural ventilation are difficult to quantify, but the potential benefits due to increased productivity can be substantial. In fact, because the cost of salary and benefits for occupants is typically several times greater than the cost of energy, even small increases in productivity (several studies estimated that productivity increased from 0.4 to 15% due to adding operable windows) can easily yield benefits that far exceed those from energy savings (Gurtekin-Celik, p.9).

NATURAL VENT

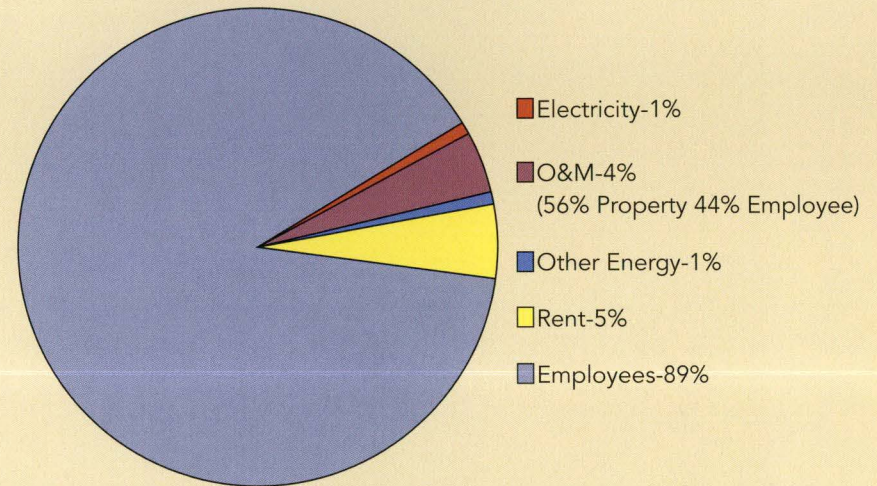
ILATION AND PRODUCTIVITY

Productivity is influenced by the physical environment (temperature, relative humidity, noise, etc.), communication and relationships, management, personal health and well-being, and stress induced by these factors. Productivity can be measured by assessments of error rates, absenteeism, and output, and by occupants' evaluations concerning their satisfaction with the work environment and their perceptions of their productivity. The linkage between improved indoor environments and productivity is convincing. Fisk estimates the productivity benefits from reduced illness in the U.S. to be worth 43 - 235 billion dollars per year (Kats, p.59).

Most of the research on ventilation and productivity has been performed with regard to mechanical ventilation. Giving occupants greater control of

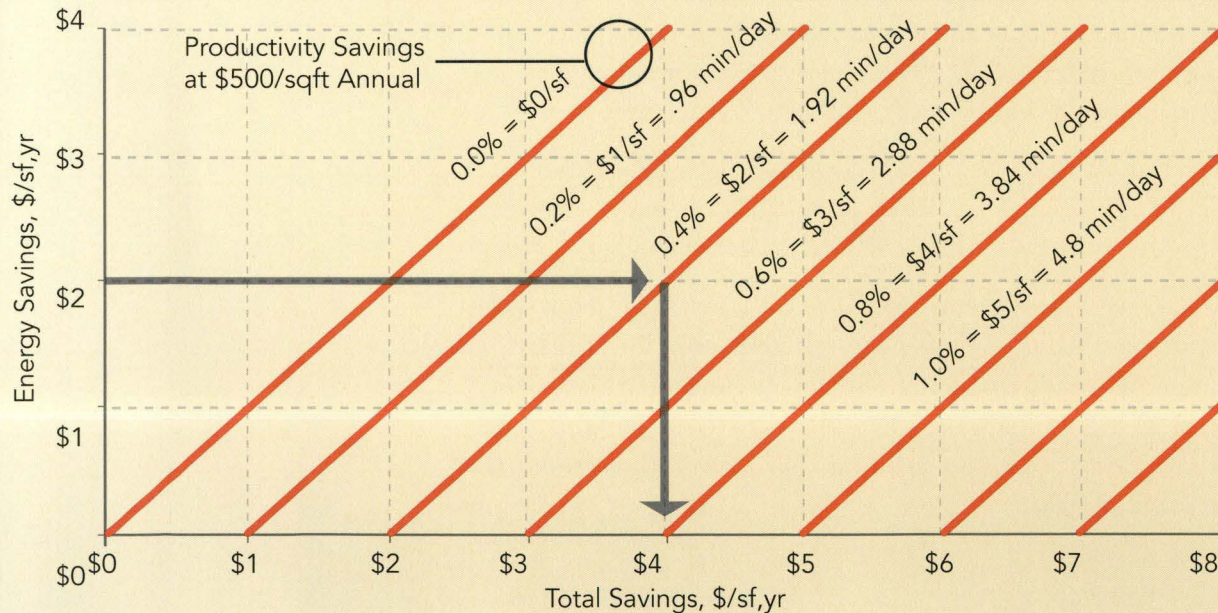
ventilation has been shown to have a positive influence on productivity, with increases ranging from .5 to 11%, with an average of 1.8%

There are few studies that directly link productivity with natural ventilation. However, Sterling found absenteeism was 3.2% lower in a naturally ventilated building than in a comparable mechanically ventilated building (Sterling and Sterling, p.387). There are studies showing fewer complaints about environmental conditions when there was direct access to operable windows. Windows for ventilation are valued by most people as either very important or quite important (Clements-Croome, p.67).



Employee Cost as a Percentage of Total Operating Costs

The argument that natural ventilation improves productivity is attractive because personnel costs far outweigh capital costs. For example, a recent evaluation of office buildings used by California state employees showed that personnel costs were 10 times greater than space costs.



Benefits of Combined Energy and Productivity Savings

The vertical axis is energy savings, the diagonal lines show rates of productivity increases, and the horizontal axis is total energy and productivity savings. In the example, if the investment in ventilation saved \$2/sf,yr in energy costs, and this resulted in a productivity increase of 1.92 minutes/day, then the productivity savings would equal the energy savings, and the total savings would be \$4/sf,yr.

Is natural ventilation cooling feasible in the Northwest?

How are natural ventilation strategies affected by concerns for comfort and air quality?

What are the upper limits of the comfort zone?

F E A S I B I L I T Y

- A building designed to use cross or stack ventilation and ceiling fans, and to have a low rate of heat gain (<100 Btu/hr/sf) can meet its cooling load with daytime natural ventilation all but 3.5% of the year in Medford (the warmest Northwest site with TMY data available), and all but less than 1% of the year in Portland and Seattle. If that building were also thermally massive, it could meet its cooling load with night ventilation in all locations, except in Medford for parts of four days, and in Portland and Seattle for part of one day. (See pages 21 and 23.)



- Designing a building to create air movement does not require an understanding of anything beyond the physics of airflow. However, ventilating a building is a more complex problem because airflow can increase or decrease both the inside temperature and the level of air pollutants, and therefore it affects occupants' perceptions of comfort and air quality. Consequently, the designer must also take these criteria, along with climate variables, into account when determining the feasibility of using natural ventilation.



- The upper limit of the comfort zone often marks the point where natural ventilation is replaced by refrigeration as the primary means of cooling a building. Since many climates in the Northwest are mild, a change of a few degrees to the upper limit of the comfort zone can have a significant effect on decisions about how to cool buildings.

WHAT CAUSES

BUILDINGS TO USE ENERGY?

Buildings don't use energy, people do.

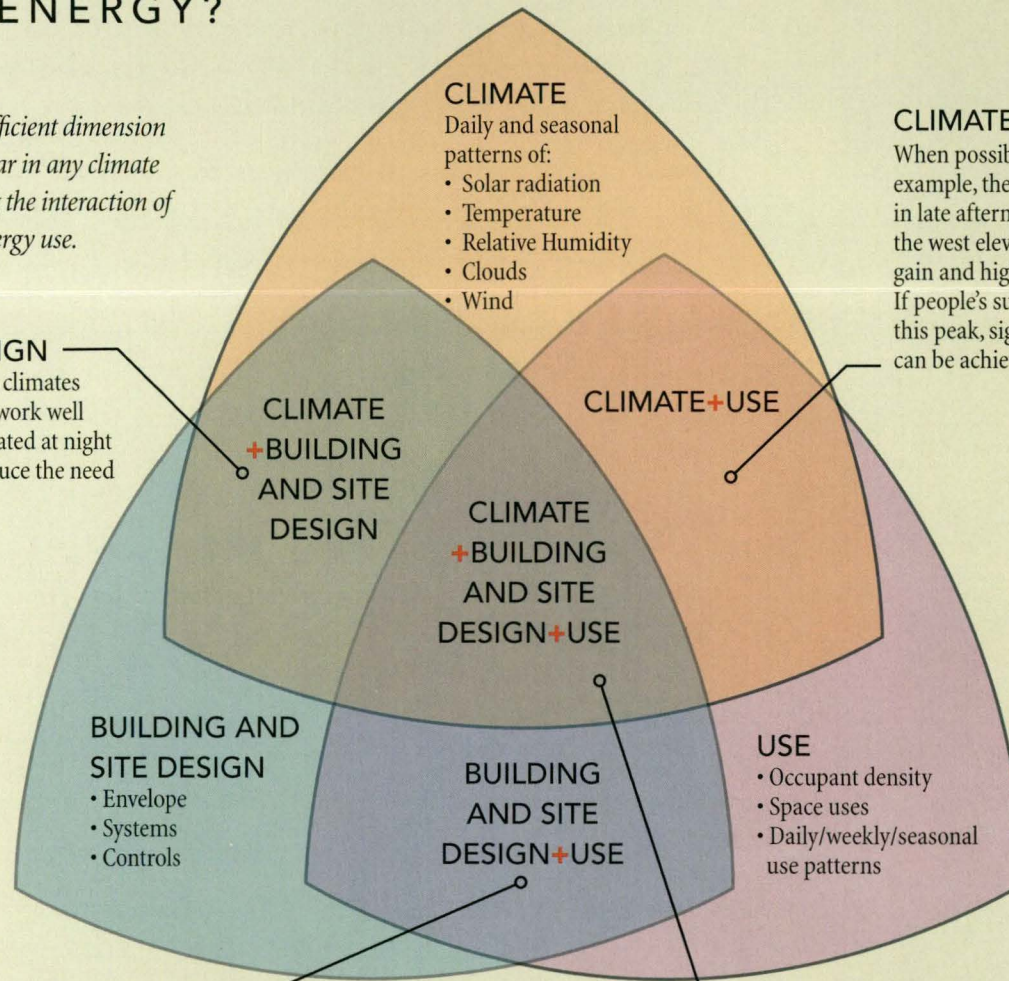
It's people's desire to have comfortable spaces of sufficient dimension to use a lot or a little at any time of the day and year in any climate that causes buildings to use energy. Understanding the interaction of people, climate, and building is key to reducing energy use.

CLIMATE+BUILDING AND SITE DESIGN

A design should work with the climate. For example, climates that have a large diurnal temperature swing usually work well with buildings that are thermally massive and ventilated at night to cool the mass, which is used in the daytime to reduce the need for mechanical cooling.

BUILDING AND SITE DESIGN+USE

A design should be sensitive to use patterns. For example, the newly planned clinic at the University of Oregon will be zoned so one third of the building can be either passively conditioned or shut down for the three summer months when there is reduced enrollment, reducing the annual heating, cooling and lighting load by 10%.



CLIMATE+USE

When possible, use patterns should follow the climate. For example, the temperature on hot summer days often peaks in late afternoon when the sun is low and perpendicular to the west elevation of buildings. This combination of solar gain and high temperature can cause the peak cooling load. If people's summer work schedules can be adjusted to avoid this peak, significant savings in first cost and operating costs can be achieved.

CLIMATE+BUILDING AND SITE DESIGN+USE

An example of taking advantage of the interaction of design, climate, and use is a building whose rooms are organized around stacks (design) with inlets and outlets designed to bring in and exhaust large quantities of cool air (climate) at night when unoccupied (use).

What are the upper limits of the comfort zone?

- The comfort zone is the range of temperatures, relative humidity, air speeds, and radiation amounts within which we feel comfortable. This comfort zone is affected by our activity level and clothing, and it also varies with age. In general, increasing activity and clothing lowers the temperature at which we feel comfortable. In general, elderly people prefer warmer temperatures.
- There has been considerable debate regarding the upper limit of the comfort zone, especially as it relates to naturally ventilated buildings. Current research indicates that the upper limit of the comfort zone for naturally ventilated buildings can be higher than that for mechanically cooled buildings. The higher acceptable limit has been attributed both to behavioral adaptations, such as decreasing clothing levels as temperatures rise, and to psychological factors, such as a relaxation of thermal expectations, a perceived control, and a greater diversity of thermal experiences in naturally ventilated buildings (de Dear).
- Using this adaptive comfort model, in the Northwest's relatively mild climates the upper limit of comfort can be 1°F to 2°F above the ASHRAE Standard 55 upper limit of 81°F at 20% relative humidity.



What are the maximum daytime temperatures at which cross ventilation can be used?

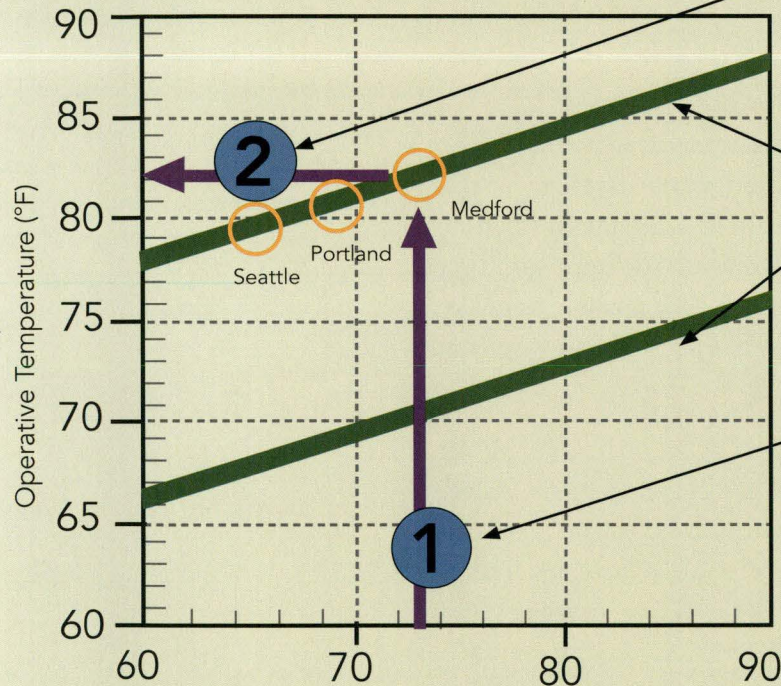
- Cross ventilation has two cooling effects: it removes heat from the space, and it increases the evaporation/convection rate of people, making them feel cooler.
- Cross ventilation air picks up heat from people, equipment, lights, etc. as it moves through the space, raising its temperature. If the space is well ventilated, the temperature increase can be 3°F or less. Therefore the maximum outside temperature allowed for cross ventilation would seem to be 3°F less than the acceptable inside temperature. However, if the cooling effect of the wind

WHAT IS ADAP

The operative temperature is defined as “the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non-uniform environment” (ASHRAE 1992, p.4).

TIVE COMFORT?

The adaptive comfort model (ASHRAE - DRAFT- 55-1992R) refers to “naturally conditioned spaces regulated primarily by the occupants opening and closing windows” and is based on the relationship of indoor or acceptable temperature ranges to outdoor climatological characteristics. To determine the upper limit of the comfort zone for the month under consideration:



2

At the intersection project horizontally to the vertical axis, which is the upper limit (operative temperature) of the comfort zone as defined by the adaptive model.

The limits of the adaptive comfort zone are a function of the arithmetic average of the mean daily minimum temperature and the mean daily maximum temperature for the month.

1

Enter the graph on the horizontal axis with the average of the mean minimum and maximum temperatures for the location, and project vertically to the highest sloping line.

Mean monthly temperature (°F)

	Mean minimum temperature for August	Mean maximum temperature for August	Average of mean minimum and maximum temperatures for August	Maximum operative temperature (80% acceptable) using the adaptive comfort model
Medford	55.4° F	90.5° F	73.0° F	82° F
Portland	57.7° F	80.5° F	69.1° F	81° F
Seattle	56.3° F	73.9° F	65.1° F	80° F

Natural ventilation - a new idea?

It's easy to think of cooling by natural ventilation in nonresidential buildings as something new and experimental, but in fact natural ventilation is historically the longest used strategy for cooling buildings. It is only in the last 70 years that buildings have been cooled by refrigeration, so it is refrigerated cooling that is new and experimental. As early as 30 B.C. Vitruvius noted the importance of a building's orientation to wind for cross ventilation. The Pantheon is an example of stack ventilation that functions effectively, regardless of the prevailing wind direction. There are numerous examples of naturally ventilated buildings in the Northwest built in the late 1800s and early 1900s. For example, the Congregation Beth Israel in Portland, Oregon, designed in 1925, uses stack ventilation to supply outside air for 1000 people who attend services. Air is drawn into a basement plenum through a grilled opening midway up the building's exterior and then distributed at floor-level locations in the synagogue. As the air is heated by the people, it rises and is exhausted through an elaborate rosette ceiling and out a roof-mounted cupola, at a rate of approximately 16,000 CFM.

What are the maximum daytime temperatures at which cross ventilation can be used?

What are the maximum daytime temperatures at which stack ventilation can be used?

How does a building's occupant use schedule affect the feasibility of natural ventilation cooling?

(from evaporation/convection) is considered, the maximum outside temperature allowable can equal the acceptable inside temperature. Cross ventilation can develop internal air speeds of up to 60% of the ambient wind speed (with continuous openings on opposite sides of a room), and an air speed of .8 miles per hour ($1.3 \text{ mph} \times .60 = .8 \text{ mph}$) results in an effective lower temperature of 3°F . Therefore the maximum outside temperature would be 82°F ($82^{\circ} - 3^{\circ} + 3^{\circ} = 82^{\circ}\text{F}$) (Brown, p. 242).



- While stack ventilation is an excellent way to remove heat from a space (lowering the indoor temperature), the resulting air change (typically 2 cfm/s.f.) does not usually increase the air movement across people enough to have a significant cooling effect. Therefore the maximum exterior air temperature possible would be the upper limit of comfort minus the increase in air temperature created as the air removes heat from the space.
- Assuming the temperature at the top of the stack is 6°F higher than the inlet air temperature, the average temperature difference between inlet and outlet is 3°F , which would also be approximately equal to the increase in air temperature in the space. Therefore the maximum outside temperature allowed for daytime ventilation would be 3° less than the acceptable inside temperature.

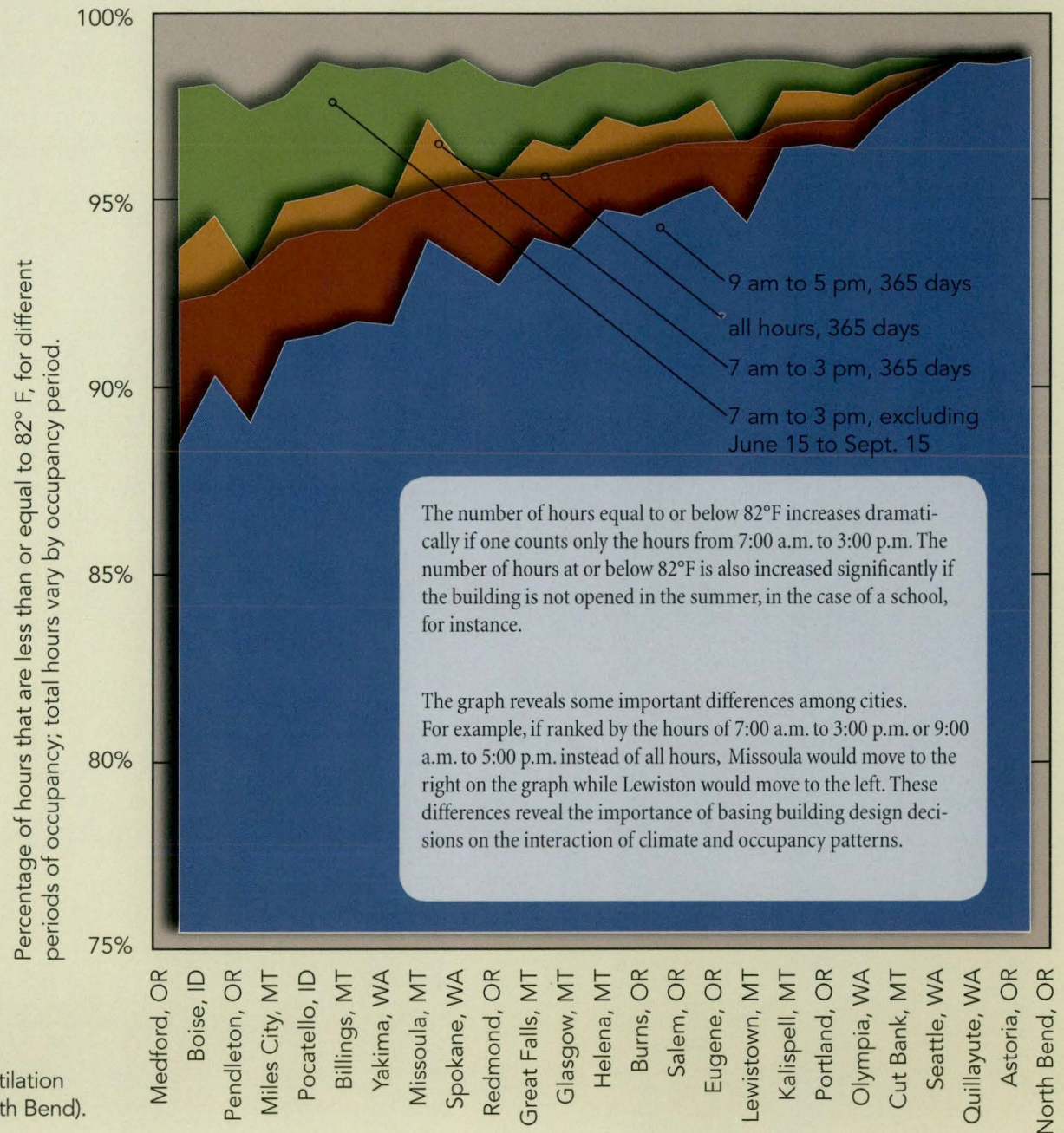


- Assuming that it doesn't negatively affect the occupants' productivity, adjusting a building's use schedule to avoid peak loads and to take advantage of climate opportunities is probably the most cost-effective strategy to reduce the cooling load and increase the feasibility of using natural ventilation.

VENTILATION

FEASIBILITY-TIME PERIOD

Since the upper limit of the comfort zone often marks the point where natural ventilation is replaced by refrigeration as the primary means of cooling a building, it is important to have people feel comfortable at as high a temperature as possible to save energy. Ventilation air picks up heat from people, equipment, lights, etc. as it moves through the space, raising its temperature. If the space is well ventilated, the temperature increase can be 3°F or less. Therefore the maximum outside temperature allowed for ventilation would seem to be 3°F less than the acceptable inside temperature. However, the maximum outside temperature can be increased as much as 3°F with air movement from ceiling fans or cross ventilation, making it possible for outside and inside to be equal $[82^{\circ} + 3^{\circ} - 3^{\circ} = 82^{\circ}]$.



Cities ranked in terms of percentage of time when cross ventilation will work for all hours, from lowest (Medford) to highest (North Bend).

How does a building's occupant use schedule affect the feasibility of natural ventilation cooling?

How can cool night temperatures be used to offset hot day temperatures?

- A thermally massive building with ceiling fans that is occupied from 7:00 a.m. to 3:00 p.m. can be cooled by day and nighttime natural ventilation almost all hours of occupation in all locations in the Northwest. The same is true of buildings, like schools, that are occupied for longer daily hours but are not operated in the summer.



- Both stack and cross ventilation can be used at night when a building is lightly occupied or unoccupied to cool mass in the building. During the day the building is closed to ventilation (except for outside air) and relies on the mass to absorb heat from both internal and external sources. Because of the low heat transfer rate between the mass and the air (1 Btu/°F, sf), large areas of mass (2-3 square feet of 4" [the optimum thickness] mass for each square foot of floor area), large volumes of air (20-30 ACH), and large temperature differences between the mass and the outside air (10-20°F) are most effective.
- Controlling heat gain is critical to a night ventilation of mass strategy because the mass's heat absorption capacity is limited. Therefore it is important to limit internal heat gain sources by using daylighting, occupancy controls for lights, fans, and plugs, and scheduling to avoid peaks, and to limit external loads by shading, increasing the envelope's resistance to heat flow, and tempering outside air with exhaust air.
- If the mass of a building is cooled at night so it can absorb heat the next day, it will remain cooler than the air temperature in the room. If the mass area is large and can be seen by the occupants so that their bodies will radiate to the mass, it will make them feel cooler by as much as 2° F or 3° F (ASHRAE 2003, p.53.4).



VENTILATION

FEASIBILITY-TEMPERATURE AND POPULATION

A key factor in determining the daytime ventilation strategy is the number of hours that the temperature in the space would exceed the comfort criteria. If the primary strategy is natural ventilation and the number of hours is zero or VERY small, then mechanical air conditioning may not be needed. If the number of hours is small, the mechanical air conditioners will not be used very often, and a system designed to economically meet the peak load, like evaporative cooling, may be desirable. Many codes require the use of economizers so that outside air can be used for cooling. Packaged rooftop units often stop using the economizer (except for outside air) at 65°F or above. This triples the number of hours needed for refrigeration cooling assuming an 82°F upper limit for natural ventilation.

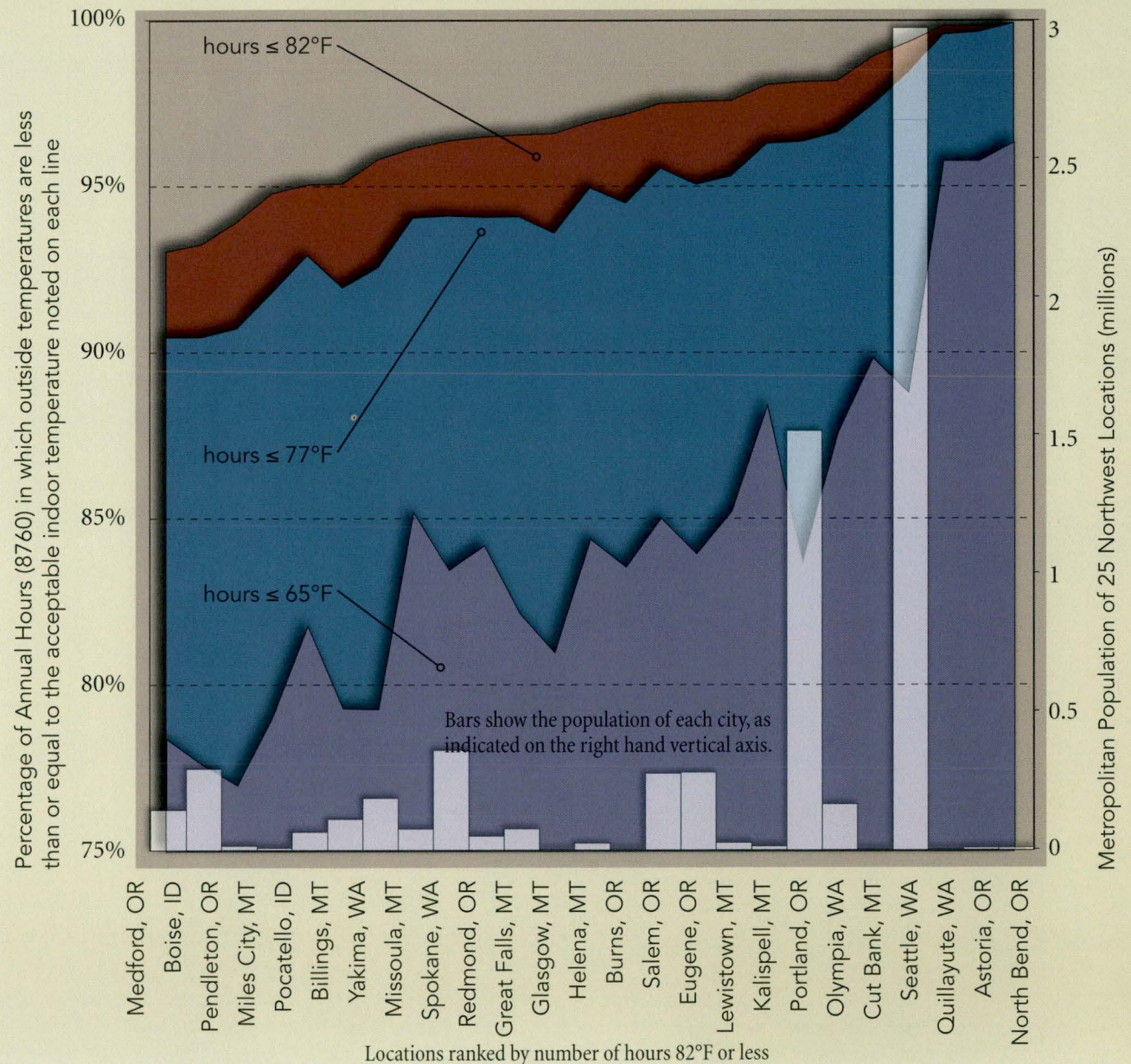
Maximum allowable exterior temperature
= top of adaptive temperature limit
+ 3°F for ceiling fans - 3°F for heat pickup:

82°F + 3°F - 3°F = 82°F for hottest climates at low RH

77°F = 80°F - 3°F for vent air heat pickup

65°F = when economizer typically turns off

The Northwest cities with the biggest populations, and therefore the most buildings, have the greatest potential for natural ventilation because they also have the greatest number of hours within the upper limits of comfort.



How does the amount of air supplied by mechanical HVAC systems differ from that supplied by natural ventilation?

What is the effect of ceiling fans on comfort and on the maximum ventilation temperatures?

- Compared to a ducted mechanical system, which supplies cool air with a large temperature difference between the supply and the room air ($\approx 20^{\circ}\text{F}$), a high velocity ($\approx 3,000$ fpm), high pressure differences ($2'' \text{ H}_2\text{O}$), and a low volume (1 cfm/sf or less), a natural ventilation system often has a small temperature difference (3° above ambient air temperature), a low velocity (88 fpm), low pressure differences ($.001'' \text{ H}_2\text{O}$), and a high volume (9 cfm/sf).
 - Moving large volumes of air for night ventilation of mass or cooling people is easier to accomplish with natural ventilation than with typical building mechanical ventilation equipment because duct and fan size and cost increase dramatically as the amount of air supplied increases.
 - Because the ducting for a mechanical air cooling system is sized for air supplied at a low temperature and cfm/sf, the economizer's ability to cool using outside air, which is at a higher temperature, is hindered by the limited duct size.
- 
- Ceiling fans increase air movement (as much as 350 fpm directly under the fan) across people, making them feel as much as 4°F cooler even though the temperature in the space does not change (Evans, p.175).
 - Ceiling fans can be used with stack ventilation to increase cooling, raising the allowable exterior temperature. However, if the stack and the fans are in the same room, the fans can compromise the stack effect by destratifying the air in the room, reducing the temperature at the top of the room and the temperature difference between the bottom and top of the stack. Ceiling fans can also be used with cross ventilation when people are not directly in the air stream or the wind speed is low.
 - Ceiling fans are effective with night ventilation because they increase the rate of heat transfer from the mass at night, lowering its temperature from 1°F to 3°F .

FEASIBILITY

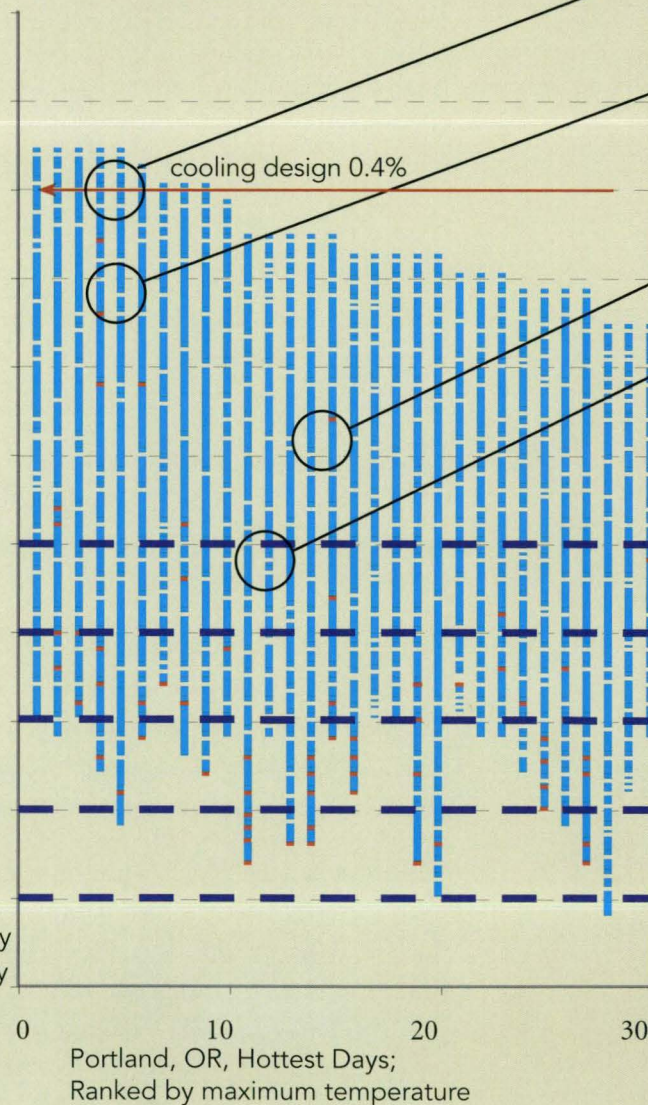
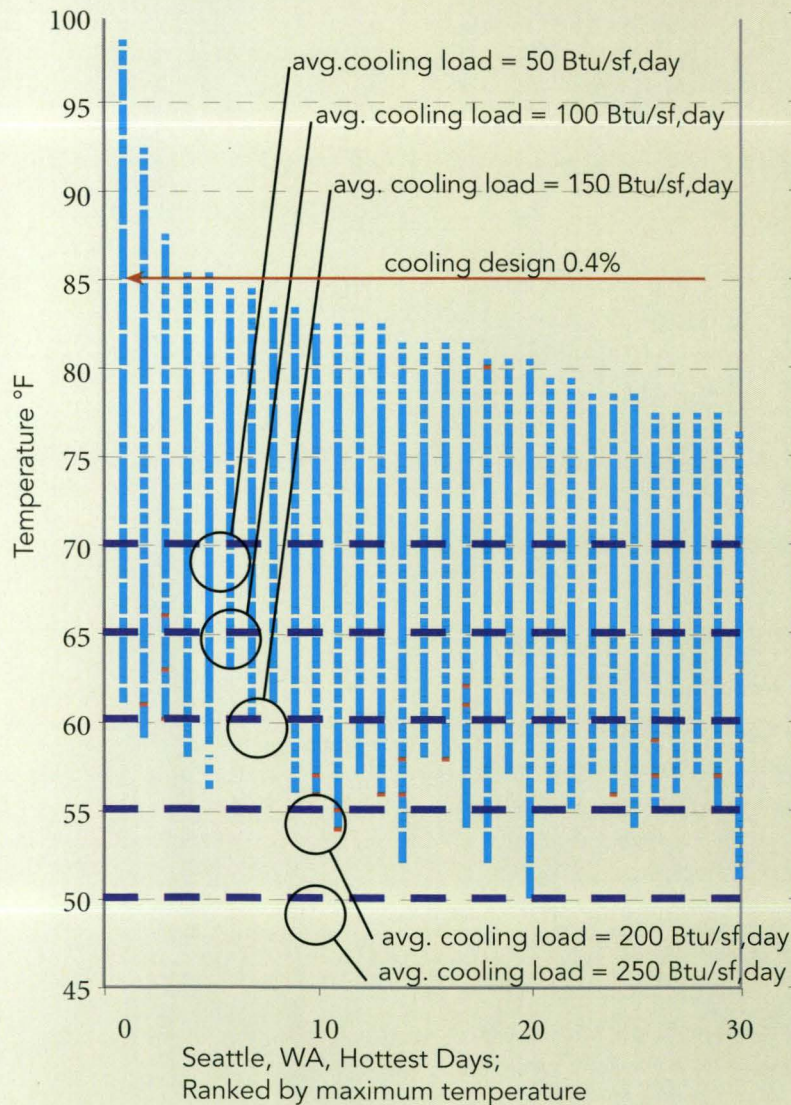
In Portland and Seattle night ventilation will meet all of the cooling load up to about 150 Btu/sf , day. In Portland nighttime wind speeds are low and therefore cross ventilation combined with stack ventilation may be a good choice for night ventilation. However, in Seattle wind speeds are more likely to be sufficient for cross ventilation at night.

In order to be effective for cooling, mass must be cooled the night before a hot day; therefore, low night temperatures are important. Because in the graph the periods start and end at 9 pm , all the lowest temperatures on each line are for the night preceding the hot day-time temperatures and indicate the potential difference in temperature between the mass and the night air and therefore the cooling capacity.

OF NIGHTTIME VENTILATION OF MASS

This graph describes the feasibility of using night ventilation to meet all or part of the cooling load of a building for several rates of gain Btu/sf, day). The amount of nighttime ventilation required to remove heat stored in the mass is determined by the amount of heat stored during the day. The heat stored during the day is a function of

internal heat gains (from lights, equipment, etc.) and external heat gains, for example from the sun. The amount of heat lost at night is a function of the outside air temperature and the amount of air that can be moved over the mass to cool it.



Assumptions

- Mass area = 2 x floor area at 4" thick
- Cool air moves across mass at 20 ACH to 30 ACH
- Max. space temperature = 80°F with ceiling fans (comfort zone = 77°F, + 3°F for ceiling fans)

*What kinds of tools
are available to
design naturally
ventilated buildings?*

*What tools are available
to analyze the climate?*

TOOLS

- Analysis tools are used to understand the problem and its context.
- Design tools or strategies are form generating—they concentrate on revealing the relationship between architectural form and both natural and mechanical ventilation (ASHRAE 2001, p.26.11).
- Evaluation tools are used to evaluate the performance of a design.
- Analysis tools are used primarily before design starts, while design strategies and evaluation tools are used iteratively during design.

Analysis Tools

- Designing successfully for natural ventilation requires knowing wind speed and direction, temperature, and relative humidity on an hourly basis for the time period the building will be ventilated.
- Typical meteorological year (TMY) data was used for this study, which is meteorological data compiled from representative months selected from 30 years of airport data. There are 25 TMY sites in the Northwest.
- Two corrections are important to adjust TMY data to a particular site: the first is for differences between the airport and the site in altitude and roughness of the terrain; the second is for local effects, such as those caused by topography, buildings, albedo, and vegetation, which create microclimates different from the airport climate.
- Wind roses are an effective means of understanding complex wind patterns. For cross ventilation it is important to know about the low velocity winds since they determine the ventilation feasibility. In some locations low velocity winds have patterns that differ from the average conditions often shown in the wind roses.

VENTILATION

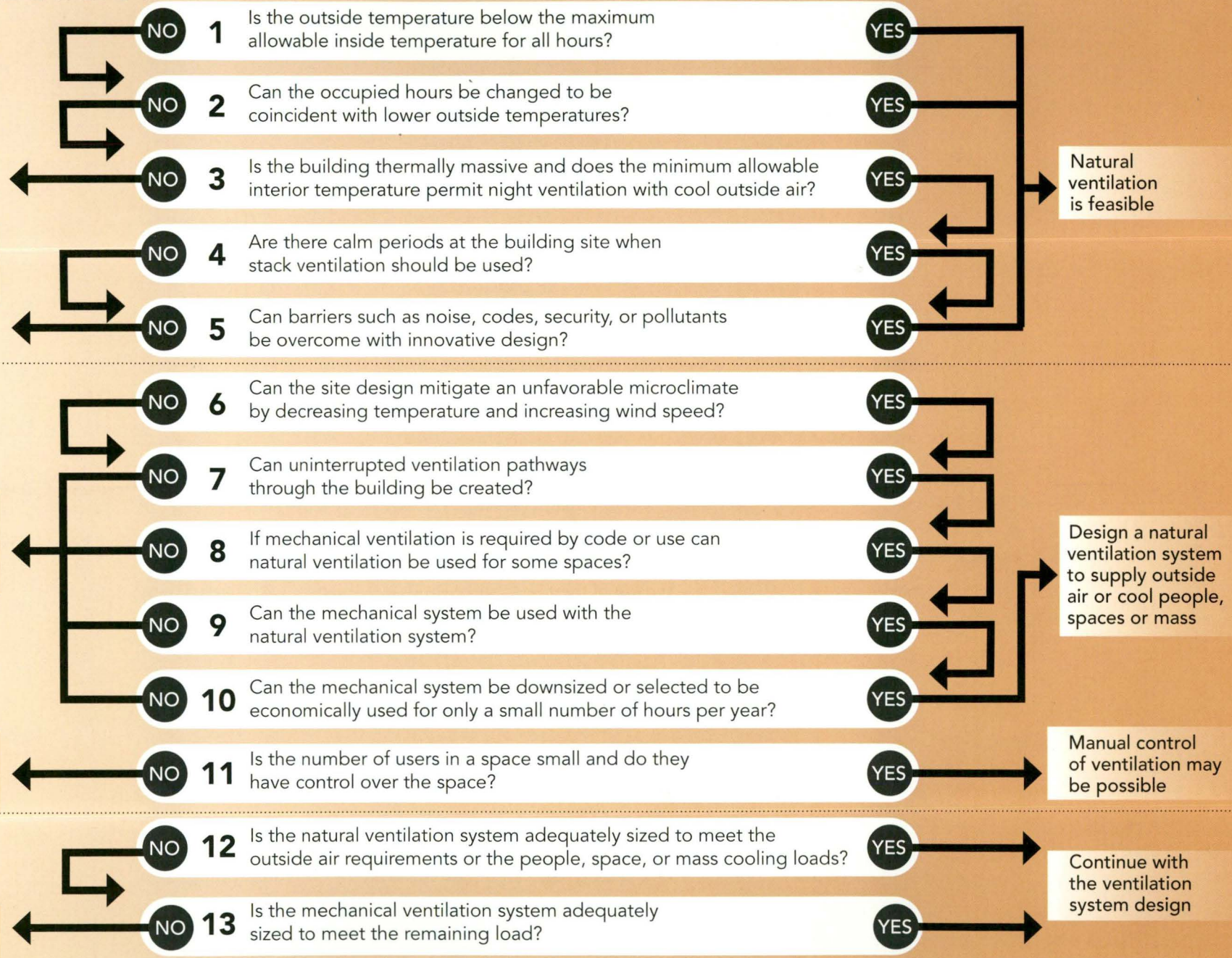
All of these questions should be addressed.

Analysis

Design

Evaluation

DESIGN CHECKLIST



What aspects of site selection and development are important for natural ventilation?

- Local topography, vegetation, and nearness to water bodies can increase wind speeds by 20% and lower temperatures by 10°F, making ventilation more effective. The reverse is also true. Sites in urban areas that are devoid of vegetation and in a wind shadow can experience wind reductions of 50% and temperature increases of 5°F (Brown, p.15).
- Because many Northwest climates have days in which hours are near the upper limits of the comfort zone, a few degrees in one direction or the other can be pivotal as to whether natural ventilation is feasible as a strategy or not. For example, a 5-degree increase in temperature from 77°F (daytime ventilation rate assuming 3°ΔT) to 82°F due to microclimate effects reduces the number of hours in Medford that can be ventilated from 8,147 to 7,850 hours, a difference of 297 hours.



What site organization strategies can be used to place buildings to maximize their potential for ventilation?

- Buildings should be placed on sites so that they take advantage of microclimates—created by trees or water bodies, etc.—that provide cool air for inlets. On sloping sites buildings should be located at the top of the slope, where winds are usually the strongest. If several buildings are to be placed on the site they should be staggered or spaced apart (about five times the building's height).

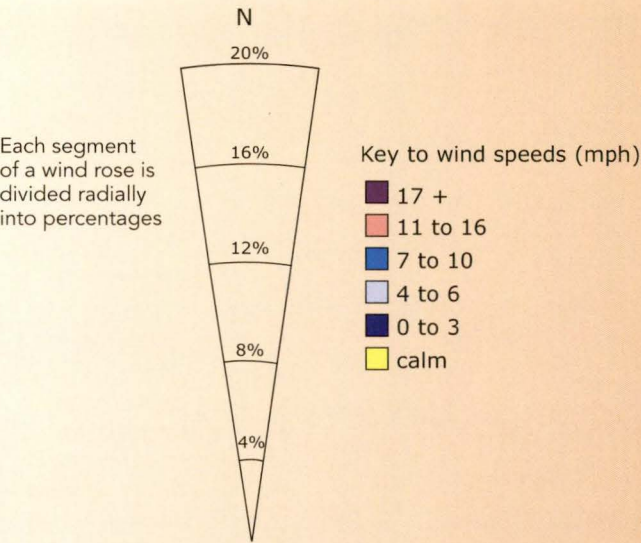


How should a building's program be analyzed for ventilation?

- When a building's program is being developed, spaces should be grouped together that have similar criteria for allowable temperature swing, rate of heat gain, occupancy density, outside air, and time of use. This zoning means similar ventilation strategies can be used in one area, while others are used elsewhere, simplifying both building and mechanical design.

WIND ROSES

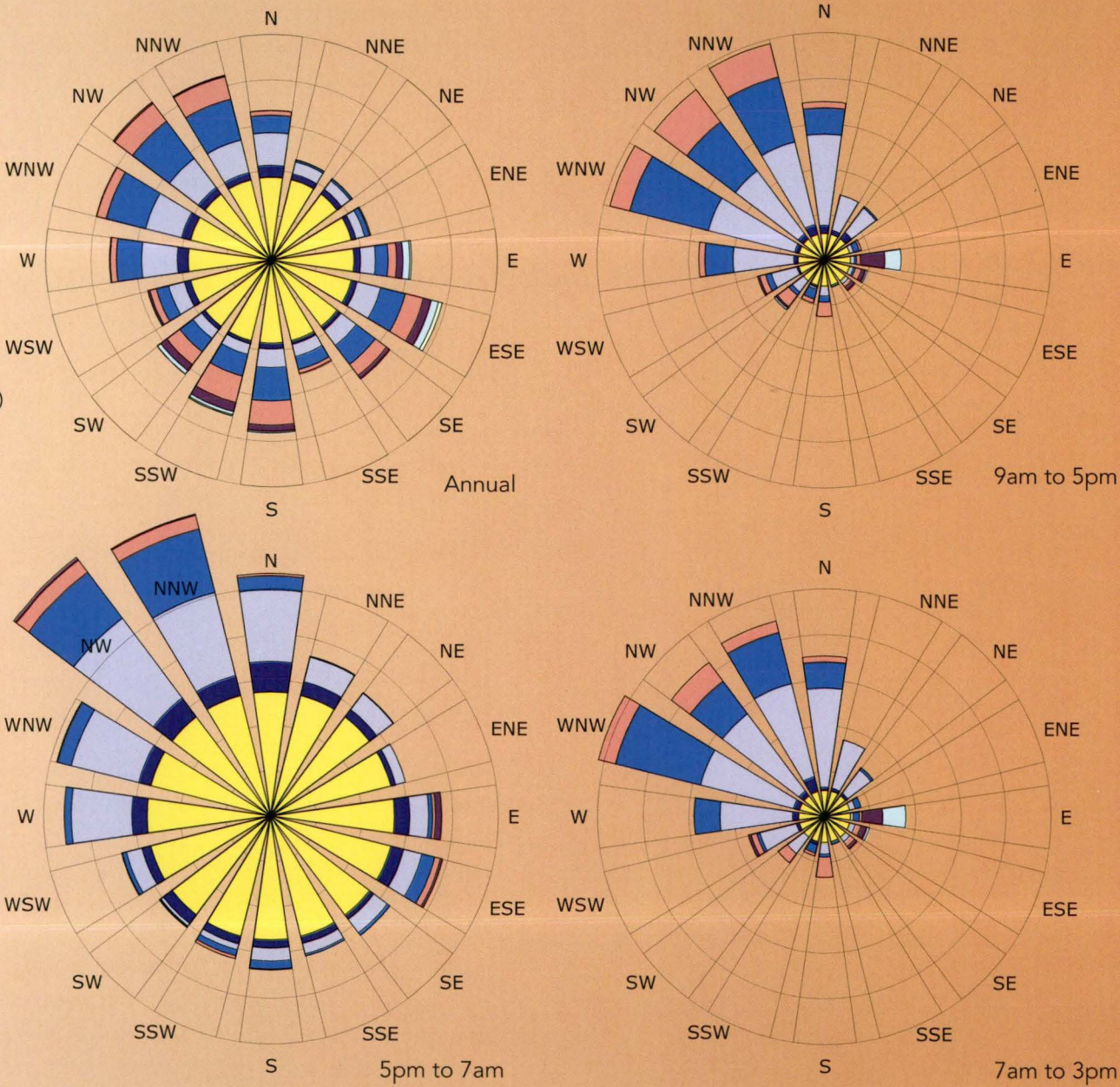
These wind roses compare the hottest 120 days in Portland for the hours 5 pm to 7 am when the outside temperature is less than or equal to 65° F (1129 hours; night ventilation), 7 am to 3 pm when the outside temperature is between 68° F and 82° F (391 hours), and 9 am to 5 pm when the outside temperature is between 68° F and 82° F (562 hours) to the annual winds for all times and temperatures (all times local time).



WHAT IS A WIND ROSE?

A wind rose gives detailed information about wind direction and frequency for a year or portion of a year. The radial bars show the percentage of the time that the wind blows from each direction for various ranges of speeds.

Wind direction varies with the time of the year and day. It is important that the wind be evaluated for the periods that natural ventilation is planned.



How should a building's program be analyzed for ventilation?

What room organization strategies are effective for cross and stack ventilation?

- Buildings that are zoned for time of use can take advantage of unoccupied periods by relying entirely on natural ventilation.
- Zoning can also reveal other compatibilities. For example, spaces that are daylighted need openings to the outside and are usually located on the perimeter, also a good location for openings for ventilation.

Design Tools/Strategies

- Room arrangement for ventilation depends upon the ventilation rate and the need for acoustic and visual privacy and security.
- The ventilation rate determines the size of the openings and their locations.
- Privacy and acoustics issues determine whether there can be openings between spaces and, if so, their size and location.
- Security issues determine both the character of exterior openings and the connections between spaces.
- Cross ventilation works well for spaces that extend from one side of the building to the other, like gyms or hallways, offering an unobstructed connection between windward and leeward openings.
- When a building is composed of many small spaces, the most straightforward way to naturally ventilate is to provide inlets and outlets in every space. Therefore, no cooperation is needed between occupants. However, limited building skin area often makes this approach impractical or too costly.
- In buildings more than one room deep and in all buildings with internal circulation corridors, the windward rooms can block the wind to leeward rooms. However, there are a number of ways to organize rooms that permit natural ventilation. For example,

ZONING FOR

The spaces that are moderately easy to ventilate would be the red, yellow, dark blue, and purple spaces, which have a small temperature range combined with either a high internal gain/low density or low gain/high density.

What room organization strategies are effective for cross and stack ventilation?

What design strategies can be used to increase the effectiveness of stack ventilation?

open office planning can be used to eliminate corridors, and if private offices on the perimeter are needed, they can be spaced apart to allow cross ventilation air to flow between them.

- Cross ventilation is a valuable means of cooling during the day, but at night air movement is frequently slow, so stack ventilation becomes an important strategy.
- Stack and cross ventilation strategies may also be used in the same building but in different rooms. For example, cross ventilation might be used in windward-side and upper-level rooms, while stack ventilation might be used in leeward-side and lower-level rooms that have little access to wind.
- It is important to keep in mind the difference in opening size for various ventilation types and the time when they are used. For example, undercut doors can allow circulation of outside air from window to room to hallway during the day when they are closed and can be left open at night for increased circulation of air past the mass.



- The rate of stack ventilation can be increased by adding a chimney to the outlet to increase the stack height. If the stack is south facing, it can be heated with the sun, which increases the average temperature in the stack and therefore the temperature difference with the outside air, increasing the ventilation rate.
- Because the pressure differences between the top and bottom of the stack are small (0.001 inches of water), they can be negated by high pressure zones created by wind flowing around the building. The performance of the outlet can be enhanced by placing it in a negative pressure area created by wind flowing over the building.



CASE STUDY

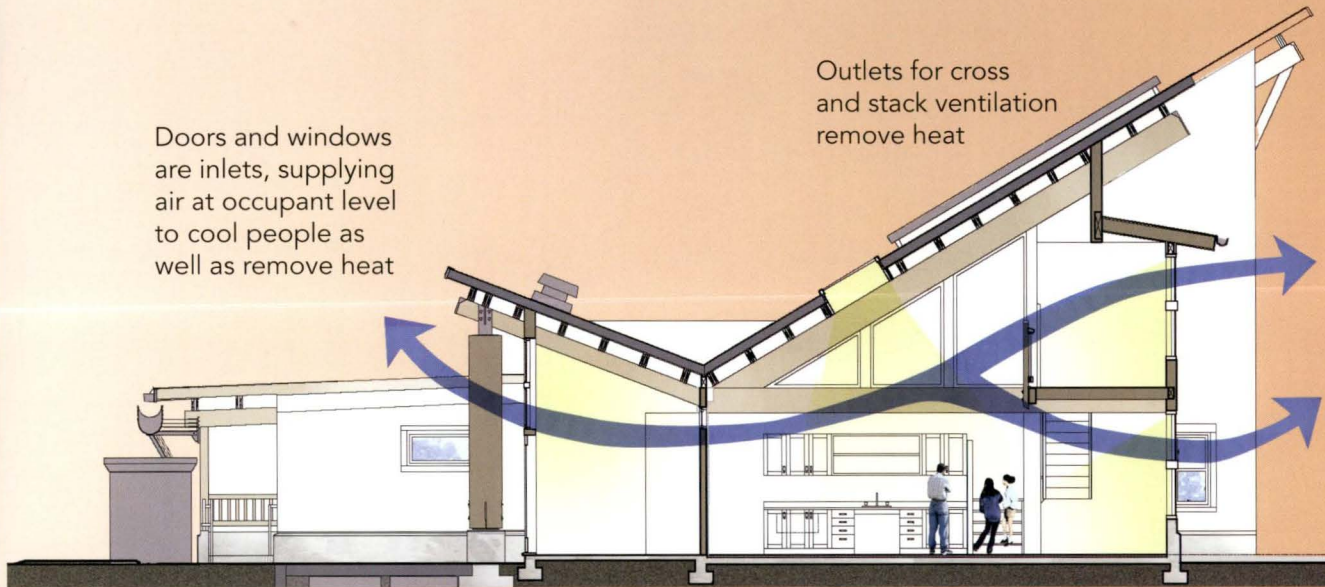


Drawings are by Mithun, Inc.
Photographs are by Art Grice.
Airflow simulation is by
Keen Engineering.

ISLANDWOOD SCHOOL

Doors and windows are inlets, supplying air at occupant level to cool people as well as remove heat

Outlets for cross and stack ventilation remove heat



		Air is moved by:		
		Cross	Stack	Fan
Ventilation is used for:	Outside Air			
	Cool People			
	Cool Space			
	Cool Mass			

IslandWood is an environmental education center for 4th grade through adult students. It is used year-round.

The building described here, the Learning Studio, uses operable windows and doors to supply outside air, cool people, and cool spaces. Ceiling fans are also used to move air across people to make them comfortable.

Location: Bainbridge Island, Washington

Owner: IslandWood

Architect: Mithun, Architects +Designers+Planners

Mechanical Design: Keen Engineering

Electrical Design: Cross Engineering



Exterior view of the corridor shown above



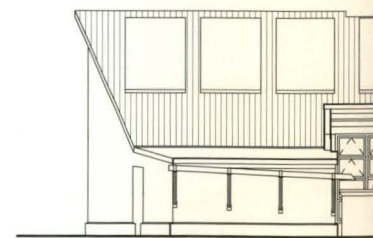
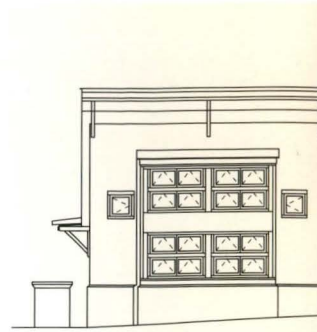
Interior view of the room in the section above

What design strategies can be used to increase the effectiveness of cross ventilation?

Can rooms with windows on only one side be naturally ventilated?

How can people and animals be prevented from entering open windows at night?

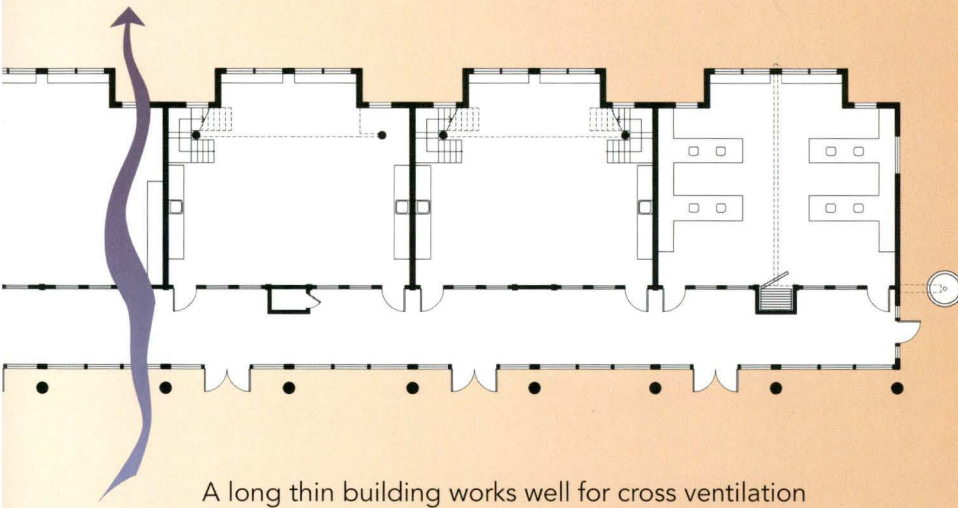
- Maximum ventilation occurs when both inlets and outlets are large and the wind is relatively perpendicular to the openings. Variations in orientation of up to 40° from perpendicular to the prevailing wind do not significantly reduce ventilation. When buildings have an orientation of 20°-45° away from the prevailing wind, it will still give one or two sides positive pressure and two or three sides negative pressure.
- When openings cannot be oriented to the prevailing breeze, landscaping or wing walls that project into the air stream can be used to alter the positive and negative pressure zones around low rise buildings to induce wind flow through windows parallel to the prevailing wind directions.
- For a room with windows on only one side, vertical fin projections can create a positive pressure at one window and a negative pressure at another. Outward opening casement windows can create a similar effect. However, wind speed within the room will be less than 20% of ambient wind speed. (Brown, p.242)
- Windows can easily be protected from entry with Mediterranean-style bars or stainless steel mesh, which looks like insect screen. Louvers also can provide access to outside air while protecting the opening from unwanted entry and rain. However, the free area for louvers or wire mesh is only 50% or less, requiring that the overall opening be larger.
- For night ventilation of spaces arranged along a double-loaded corridor in which security is important, grill or mesh can be used within an operable panel in the primary door.



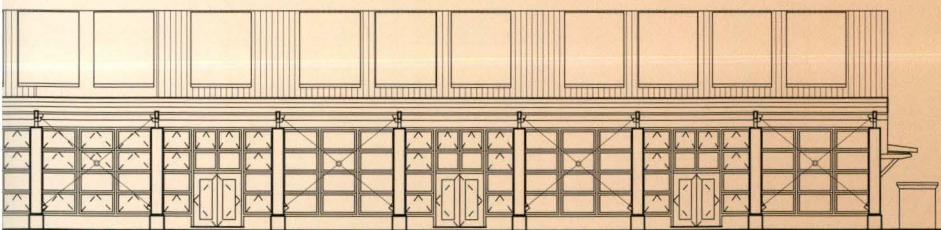
PREDICTING CROSS AND STACK VENTILATION AIRFLOW

These graphs show simulated airflow due to cross and stack ventilation through the Learning Studio (since only two of several zones are shown, the total flow in does not equal the total flow out). The simulations are for a worst-case day where wind velocities are between 0 m/s and 4 m/s.

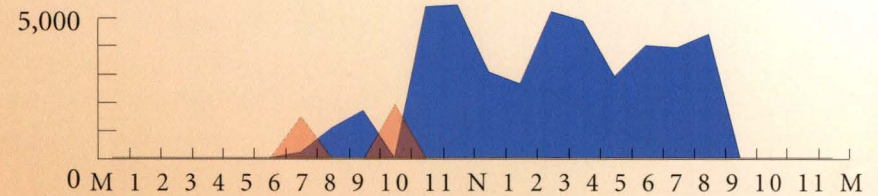
North Elevation



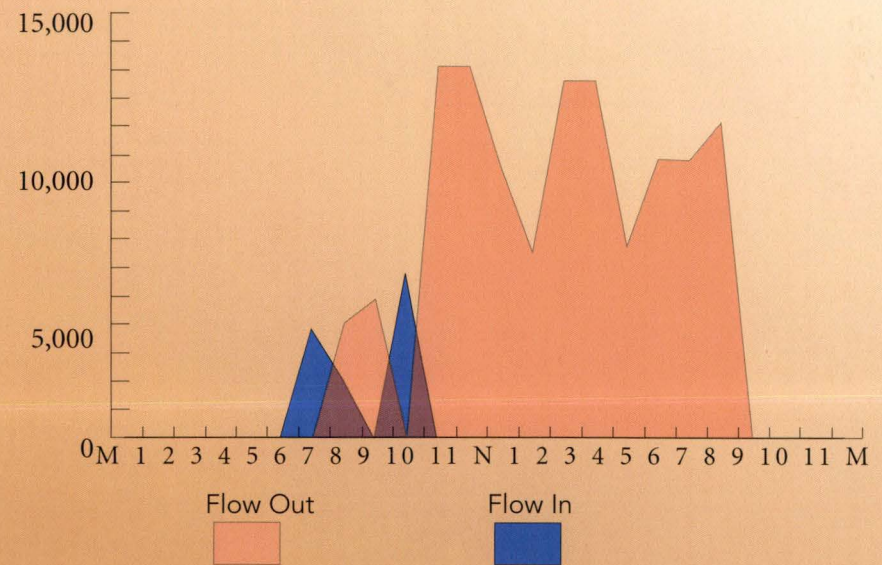
South Elevation



Airflow through a typical room zone (cfm)



Airflow through the corridor zone (cfm)



Should ventilation openings have automatic or manual controls?

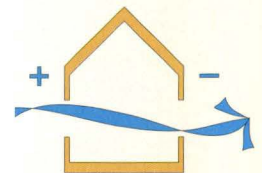
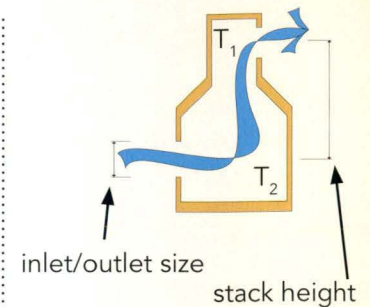
What design strategies can be used to combine natural ventilation and HVAC systems?

- The certainty of automatic controls under normal operating conditions makes them very desirable. However, in buildings with dispersed inlets and outlets they become expensive and vulnerable to power failure. They also preclude occupants from having control over their own environment, which some say is important to productivity.
- Manual controls (motorized or not) can provide the opportunity for some occupants to have control. Manual controls work best under the following conditions: when occupants have an interest, have control over their own environment, have ownership of the openings they are expected to control, know when the openings should be open/closed, and derive benefits when they operate them correctly (i.e., are comfortable).



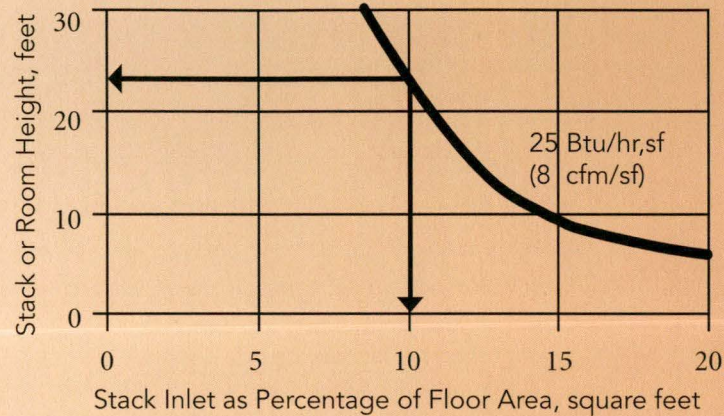
- Perhaps the most important consideration in selecting and sizing HVAC systems is the degree to which they are redundant to the natural ventilation systems. The most conservative but costly approach is to design both the natural ventilation and HVAC systems to handle all the loads, so that either system can be used.
- It is important that the controls prevent natural ventilation inlets or outlets from being opened when heating or cooling is being provided. This can be accomplished by either letting occupants know when it is okay to open windows or by automatically shutting down the HVAC system when windows are opened.
- If a building is designed to use natural ventilation for outside air, space and mass cooling, daylighting, and other strategies to reduce internal and external heat gains, the loads can become very small so that the number of hours mechanical cooling is required

STACK AND C



CROSS VENTILATION

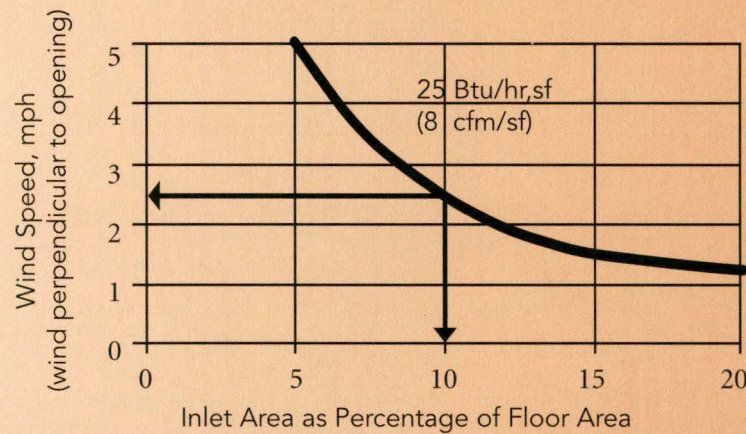
With stack ventilation, the rate at which the air moves through a room carrying heat with it is a function of the vertical distance between the inlets and outlets, their size, and the temperature difference between the outside air and the average temperature in the stack. The ventilation rate is most sensitive to inlet/outlet size except for with stack heights below 15'.



$$Q_s = 60 C_D A \sqrt{\frac{2g \Delta H_{NPL} (T_i - T_o)}{T_i}}$$

Q_s = stack vent airflow rate, cfm; A = cross-sectional area of opening, ft²; C_D = discharge coefficient for opening; ΔH_{NPL} = height from midpoint of lower opening to NPL, ft; T_i = average indoor temperature between the inlet and outlet, °R; T_o = outdoor temperature, °R; NPL = neutral pressure level, location/s in the building envelope where there is no pressure difference between inside and outside (ASHRAE 2001, p.26.11).

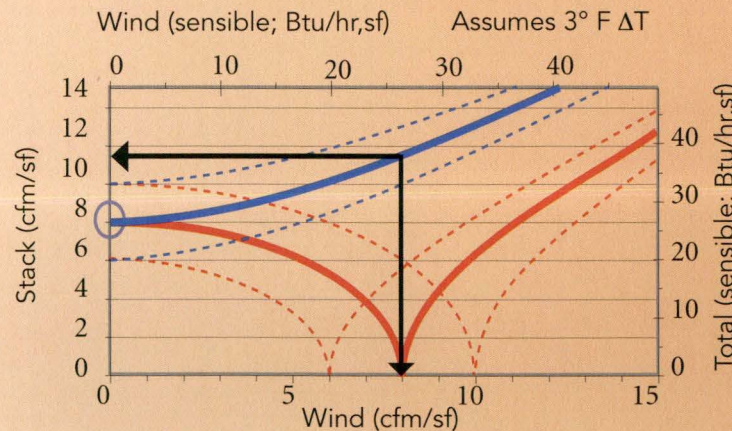
Cross ventilation's efficiency is a function of the building's form, orientation to the wind, and room organization, all of which determine the magnitude of the pressure difference between windward inlets and leeward outlets and their connection. The cross ventilation rate is sensitive to wind at low speeds and opening sizes at high wind speeds.



$$Q_w = C_4 C_v A U$$

Q_w = cross vent airflow rate, cfm; C_v = effectiveness of openings (assumed to be 0.5 to 0.6 for perpendicular winds and, 0.25 to 0.35 for diagonal winds); A = free area of inlet openings, ft²; U = wind speed, mph; C_4 = unit conversion factor = 88.0 (ASHRAE 2001, p.26.11).

Cross and stack ventilation can work together, although the ventilation rates are not simply additive. When wind flows around a building it creates positive and negative pressure zones. If the inlets for stack ventilation correspond to the high-pressure zones and the outlets to the low-pressure zones, then wind will assist the stack ventilation (the blue line on the graph). If the reverse is true, the wind will offset the stack ventilation (red line). For example, for stack and cross flow rates of 8 cfm/sf, if the wind is assisting the total flow will be about 12 cfm/sf, and if opposing the stack flow will be 0 cfm/sf.



The combined rate is:

$$Q = \sqrt{Q_s^2 + Q_w^2} \quad \text{for wind assisted, and}$$

$$Q = \sqrt{Q_s^2 - Q_w^2} \quad \text{for wind opposed.}$$

Q = cfm combined; Q_s = stack vent airflow rate, cfm; Q_w = cross vent airflow rate, cfm (ASHRAE 2001, p.26.21).

What design strategies can be used to combine natural ventilation and HVAC systems?

What strategies are available to augment natural ventilation with mechanical ventilation?

is also small. The cost of mechanical cooling then becomes very high per hour used, which drives the mechanical cooling system towards inexpensive methods of meeting peak loads.

For example:

If outside air ventilation can be introduced at the building skin (making ducts unnecessary), then water as a heat transfer medium becomes more attractive for heating and cooling, reducing distribution costs and making a drop ceiling less necessary, which is important for mass cooling.

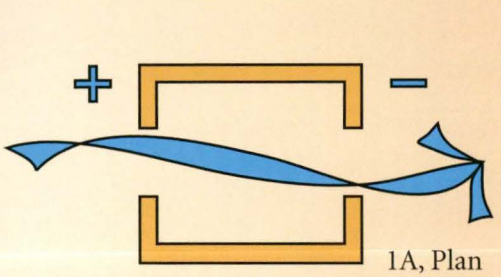
If the cooling load has been substantially reduced by day and night ventilation in climates with high heating loads, radiant panels used for heating may be big enough to meet the cooling load even though the panels can't be cooled so much as to cause condensation.

For many Northwest climates evaporative cooling is an inexpensive way to extend the cooling capacity of natural ventilation at the peak period, especially if intake air is centrally located so that misters can be economically used.

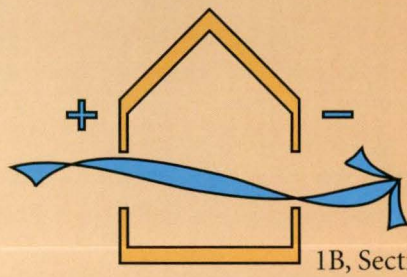
- Mechanical ventilation makes sense as an assist to natural ventilation in many cases. It is a way to dependably introduce a high rate of outdoor air into buildings at a relatively low rate of energy consumption compared to air conditioning. Mechanical ventilation inlets can be positioned at higher elevations, where air may be cooler (depending on the roof surface) and cleaner. Air can also be filtered to remove pollutants, and a heat exchanger can be more easily applied than with natural ventilation alone.

SINGLE ROOM

BUILDINGS

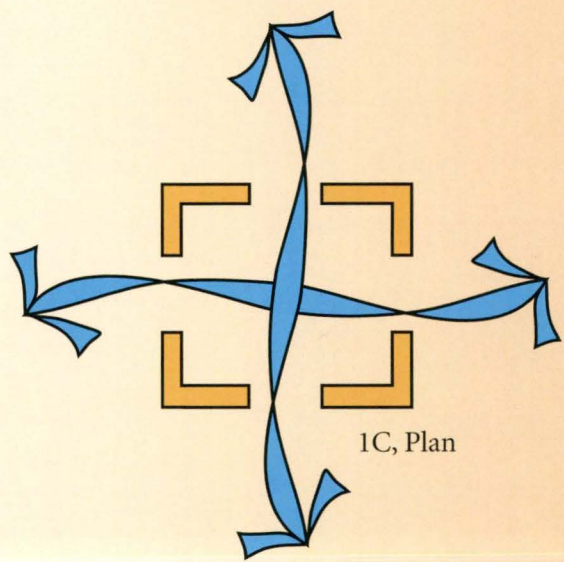


1A, Plan

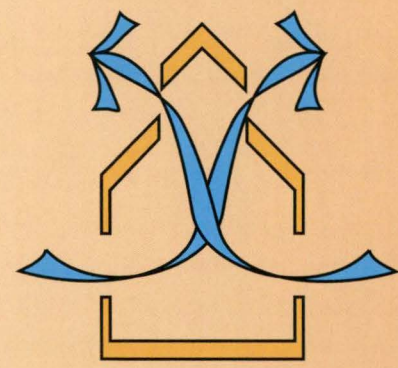


1B, Section

One-room buildings such as barns (1A, 1B) exemplify what is required for natural ventilation. If they have an opening on the windward side (high pressure) and an opening on a leeward side (low pressure), air will flow through the space from the high pressure to the lower pressure opening, cross ventilating the building.



1C, Plan



1D, Section

If there are openings on all four sides (1C) the building will cross ventilate regardless of wind direction. In the absence of wind and when the air inside the building is warmer than outside, the warm air will rise to the top of the space because it is lighter and more buoyant. If there is an outlet in the roof, the warm air will be exhausted and be replaced by cool air flowing in the bottom windows, stack ventilating the building (1D).

CROSS AND STACK VENTILATION BUILDING DESIGN STRATEGIES

To cross and stack ventilate a building there must be openings. When a building has more than one room, there must be openings between the rooms, as well as to the exterior, so that air will be able to flow through the building. Inlets and outlets can be concentrated in one location, clustered in several locations, or dispersed throughout the building. Inlets and outlets that are dispersed have the advantages of individual controls and even distribution of air for cooling for people, but they have the disadvantage of higher maintenance and first costs of multiple openings. Concentrated or clustered openings can be less expensive and easier to control automatically, but even distribution is sometimes more difficult. Inlets and outlets can be located in the same room or in rooms that are separated by walls or even other rooms. Inlet rooms and outlet rooms that are separated by a wall can be ventilated if the rooms can be connected by an opening. Inlets that are separated from outlets by several rooms require more ingenuity.

What kinds of evaluation tools are available?

What can physical models do?

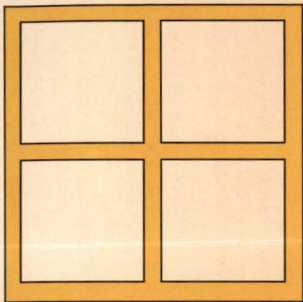
What are the simplest numerical evaluation tools to use?

Evaluation Tools

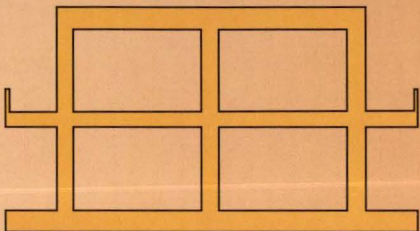
- The purpose of evaluation tools is to enable the designer to understand how well a proposed building ventilation system design will work. These tools/methods use physical or mathematical models. Some tools combine thermal and ventilation models.
 - When selecting a tool, the designer must consider its form (non-computerized or computerized), the costs both to purchase and use the tool (time, expertise), which effects need to be accounted for (ie., single vs. multi-zone, heat sources, pollutant transport, mechanical systems, and others), and what data is available.
 - The tools chosen need to be appropriate to the design phase as well as the problem. For instance, a zonal airflow model could indicate bottlenecks in flow caused by opening sizes between rooms in design development, while a computational fluid dynamics model could be used to demonstrate the effectiveness of difficult stack outlet configurations towards the end of design development or at the start of creating construction documents.
- 
- Physical modeling using a wind tunnel is useful in situations where the natural ventilation design or application may not be modeled accurately or at all by other means, and in some cases it may be simpler and less expensive than computer analysis. A wind tunnel allows airflow patterns around buildings and within spaces to be visualized as well as measured.
- 
- Empirical and simplified theoretical methods use air-tightness data or simplified algorithms and include wind velocity and temperature-driven flow effects. More complex models account for terrain effects and shielding, as well as mechanical systems drivers. They provide fast ballpark estimates and can be expressed

MULTI-ROOM

BUILDINGS

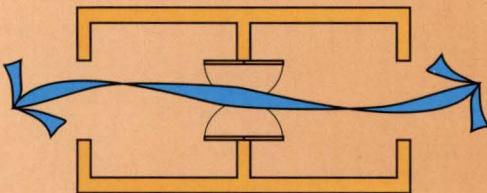


2A, Plan

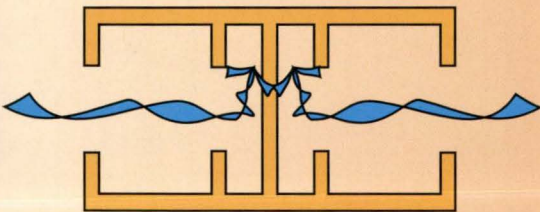


2B, Section

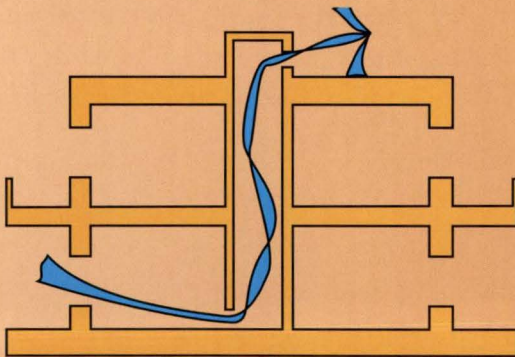
Rooms arranged back to back with exterior circulation in buildings more than one story high (2A and 2B) can be night ventilated if opened to each other at night and cross ventilated to cool the mass (2C). The openings can usually be the size of one or two doors and can achieve good acoustic separation when closed. Security, if necessary, can be achieved using the same screens and grills as used in exterior windows.



2C, Plan



2D, Plan



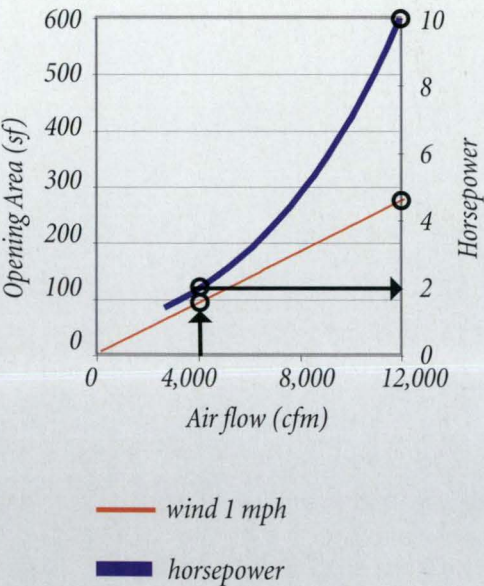
2E, Section

This approach does not work for daytime cooling or outside air if acoustic separation is important. Individual stacks can also be created in each room. The size of the stack will vary considerably depending on the ventilation type. However, if the shafts are sized for daylight they will usually be large enough for all forms of ventilation (2D and 2E).

Windows or Fans

If the windows in a building are operable and are arranged to facilitate cross or stack ventilation, they can move a large volume of air. For example, used as inlets and outlets, windows with an opening area of 100 square feet each, with a wind speed of 1 mile per hour, will create an air flow of approximately 4,000 cfm, roughly equal to what a 2 hp fan could move. To raise the cfm by a factor of 3 to 12,000 cfm, it would require an inlet and outlet window area of 275 square feet, or about 2.75 times the size of the original window. To realize the same increase in air movement with a fan would require a 10 hp fan, or about 5 times the size of the original.

Temperature Assumptions: $T_i=80^{\circ}\text{F}$, $T_o=77^{\circ}\text{F}$, and $\Delta H=\text{neutral pressure level assumed to be } 1/2 \text{ the stack height}.$



What are the simplest numerical evaluation tools to use?

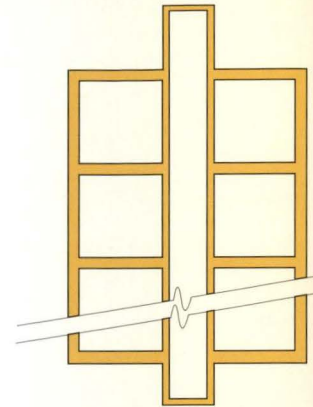
What are network-based evaluation tools?

What are zone-based evaluation tools?

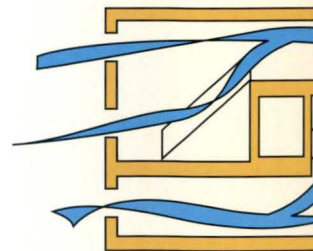
as a rule-of-thumb, nomographs, or calculation routines, but are limited to a single zone. They are narrowly derived and therefore should be used carefully within the limits of theory or experimental data. They do not account for characteristics that vary over time, and they do not determine airflow direction.

- Network methods are versatile tools that predict bulk flow using models that represent spaces and the exterior as a series of zones, and connecting windows, doors, and other openings as airflow paths. Given exterior wind pressures, the unknown pressures within each zone are calculated using mass balance equations across flow paths. These models can be single- or multi-zone. The explicit or inverted form of network modeling solves the algorithms backwards and is used to size openings for stack or cross ventilation.
- Network models do not predict distribution of temperature or air velocity within a zone; they assume well-mixed zones and so do not account for stratification. These models have limited usefulness in predicting comfort conditions as comfort depends on temperature, relative humidity, and air velocity distributions.
- Zonal methods are an intermediate step between network modeling and computational fluid dynamics (CFD) modeling. Spaces are divided into individual macroscopic horizontal and vertical zones, and equations are solved using mass and energy equations and by adding simple momentum equations. Zone based models provide more information than network models and with less effort than with CFD modeling.

DOUBLE-LOAD

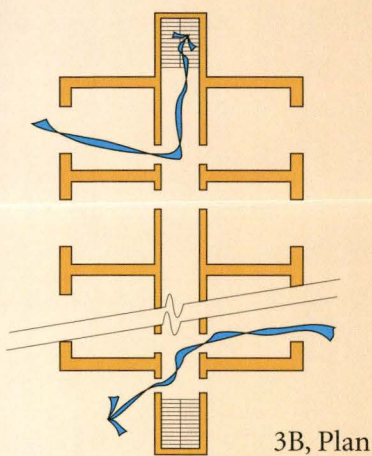


3A, Plan

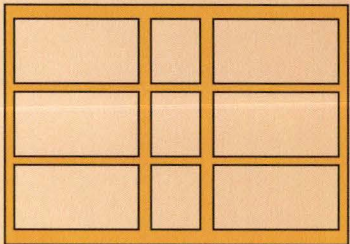


3D, Section

ED CORRIDORS

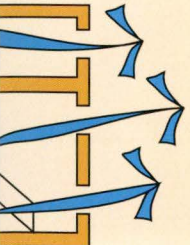


3B, Plan

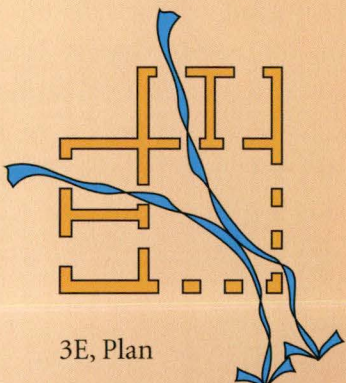


3C, Section

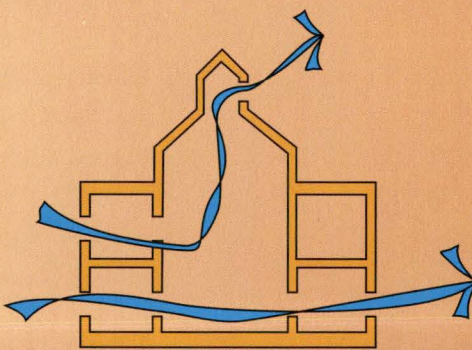
Probably the most common problem for natural ventilation is the double-loaded corridor (3A and 3B). They can be ventilated with a stack in each room, as shown in 2D and 2E, or they can be night flushed using the stairwell as an exhaust stack (3C). If required for fire protection, room doors as well as stair doors can be on electronic holdopens. Outside air requirements can often be met with the doors shut by using the undercut as a passageway to the corridor and the stair shaft. Cross ventilation, especially night flushing, can be provided by grilled openings in each door so the wind can flow into rooms on one side and across the corridor to rooms on the other side. Cross ventilation can also move across a single room and along the corridor to an open stairwell (3C). The use of exits and exit access corridors as supply or exhaust plenums for mechanical systems is restricted by the mechanical code.



A more exotic solution (3D) provides circulation at every third floor, allowing cross ventilation through each space.



3E, Plan



3F, Section

Atriums are like wide corridors/stairs in that they can be cross or stack ventilated at night by opening doors into the atrium (3E and 3F).

What are computational fluid dynamics evaluation tools?

What are the benefits of tools that combine ventilation and thermal models?

- Computational fluid dynamics (CFD) methods subdivide spaces into many small volumes, and mass, energy, and momentum equations are solved by iteration. This results in predictions of two- and three-dimensional patterns of air flow within the spaces being analyzed. CFD tools can solve steady state or transient problems. Specific applications include simulation and prediction of room air flow, air flow in large spaces such as atria, air change efficiency, pollutant removal, temperature and air velocity distribution such as needed to predict comfort, and air flow around buildings.
 - CFD modeling requires a great deal of expertise and effort to get good results. It is costly to buy and time intensive to use, and the degree of complexity that can be handled is limited by available computing resources. In some cases free and forced convection are not directly linked.
- 
-
- 
- Combination ventilation/thermal models integrate a thermal or energy model with a ventilation model (traditional energy models often oversimplify ventilation, which compromises the reliability of their results in this regard). These tools aid in understanding how ventilation affects the thermal performance of a building, both as a whole and within components of the building, and how ventilation affects thermal comfort. These tools are also useful for designing building energy management systems. However, these tools are very complex, requiring expertise to use them appropriately and accurately.

WHAT KIND OF EVALUATION TOOL?

Airflow Rates

Airflow Patterns

Building Energy

Indoor Air Quality

Comfort

WHAT ARE YOU TRYING TO FIND OUT?	TYPE	DESIGN STAGE	EFFORT	INPUTS REQUIRED	FORM	SEE REFERENCE #
building vent rate or mean air velocity, average air infiltration rate, building air change rate	Empirical and Simplified Theoretical	early	very little	Weather data such as wind and temperature, exterior openings (these inputs are common to all tools)	graphical, rule-of-thumb, simplified, generally non-computerized	23 p200, 6 p64, 24 p2
average airflow rate and direction, and temperature for each zone; window sizes needed in the case of inverted modeling	Network	early	some	interior airflow openings, internal heat gain sources, fan and duct descriptions	computerized	23 p205, 6 p89, 24 p1
	Zonal	middle	a fair amount	interior airflow openings, zone and flow path information, internal heat sources	computerized	6 p114
visualizations of airflow and temperature distribution inside and outside of a space/building	Physical	early	some	building or room geometry and openings	physical model, photographed during test with smoke or other visualization media	14 p649
	Computational Fluid Dynamics	middle	a lot	similar to zonal models but with many more volumes	computerized	23 p219, 6 p119
thermal model graphs and tabular data describing energy, temperature, and other variables	Ventilation and Thermal	middle	a lot	data for ventilation, detailed building, lighting and HVAC systems, and occupancy data for the thermal model	computerized	23 p228, 24 p2
pollutant flow and concentrations, and back drafting risks	Empirical and Simplified Theoretical	early	some	weather data (wind, temperature), exterior openings	graphical, rule-of-thumb, simplified, generally non-computerized	23 p200, 6 p64, 24 p2
	Network	middle	a fair amount	interior airflow openings, internal heat gain sources, fan and duct descriptions	computerized	23p 205, 6 p89, 24 p1
	Ventilation and Thermal	middle	a lot	data for ventilation, detailed building, lighting and HVAC systems, and occupancy data for the thermal model	computerized	23 p228, 24 p2
thermal comfort predictions	Zonal	middle	a fair amount	interior airflow openings, zone and flow path information, internal heat sources	computerized	6 p114
	Computational Fluid Dynamics	middle	a lot	similar to zonal models but with many more volumes	computerized	23 p219, 6 p119



This table provides guidance on selecting tools to model natural ventilation. There are good online resources for information about these types of tools, how to use them, and specific tools (references 9, 31).

*Aren't naturally
ventilated buildings
more expensive?*

*Aren't the components
needed to design and
construct naturally
ventilated buildings
difficult to find?*

B A R R I E R S

- Naturally ventilated buildings can be more expensive if they have high cooling loads that cannot be mitigated by architectural design, if they cannot be configured to use natural ventilation effectively, or if they require completely redundant mechanical and natural ventilation systems. While these situations are common, they do not apply to the majority of the buildings in the Northwest.
- What is required to create naturally ventilated buildings that have operating costs that make their construction cost investment worthwhile is a team of owners, users, architects, and engineers that: 1) carefully consider comfort criteria by activity; 2) zone the building program in terms of use patterns and natural ventilation criteria; 3) design the building to create small loads; and 4) use efficient equipment to meet those loads.
- There are a number of programs in the Northwest that are designed to reduce the first cost of constructing energy-efficient buildings. In Oregon, design assistance and/or incentives are available from the Northwest Energy Efficiency Alliance's BetterBricks program, the Energy Trust, some utilities, and the Oregon Office of Energy. In Washington, design assistance is available from the State Department of General Administration and some utilities.
- Shades and operable windows and vents are readily available in the United States. However, a much greater variety is available in Western Europe, where load minimization and natural ventilation are more the norm. As the market for naturally ventilated buildings increases in the U.S., these products should become more available here. Controls and vent opening operators are available, but are not always designed or constructed for commercial building use.

CASE STUDY



South Elevation



Northeast Corner

Atrium outlets; stack vent dampers and HVAC system linked through building control system to control building exhaust



Operable office windows for vent air and cooling; inlet below office window; radiant fin tube system can temper incoming air



LILLIS BUSINESS COMPLEX

		Air is moved by:		
		Cross	Stack	Fan
Ventilation is used for:	Outside Air		1,3,4	1,2,3
	Cool People		3,4	2,3
	Cool Space		1,3,4	1,2
	Cool Mass		1,4	1,2

1–Lecture Hall and Auditorium; 2–Mixed Mode Classrooms; 3–Mixed Mode Offices; 4–Atrium

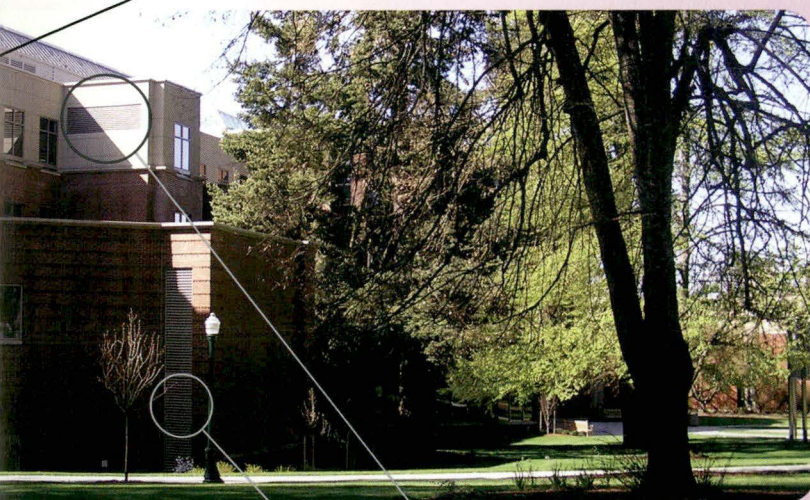
The Lillis Business Complex is a four-story, 140,000 sf building containing offices, classrooms, lecture hall, auditorium, and an atrium. Besides the ventilation features, the building utilizes daylighting, efficient electric lighting, grid-tied (standard and building integrated) photovoltaics, east-west orientation, and lighting and shade controls.

Stack ventilation and HVAC fans supply outside air, provide modest space cooling, and cool the building mass in the lecture hall and auditorium. Dampers are automatically operated by the building control system. In addition to stack ventilation, HVAC fans supply conditioned outside air, space heating and cooling, and mass cooling. The lecture hall and auditorium have their own HVAC system.

Most classrooms have a system to supply minimum outside air, modest space cooling, and modest mass cooling without going through the HVAC system. Dampers and the transfer fan speed are automatically set by the building control system. In addition to this fan system there is a backup HVAC system to supply conditioned outside air, space heating and cooling.

(con't.)

Offices



Ceiling fans in offices to cool people



Lecture and auditorium inlet

Lecture and auditorium outlet

Won't undesirable outside conditions such as high temperature, pollen-laden air, or noise reduce the productivity of building occupants?

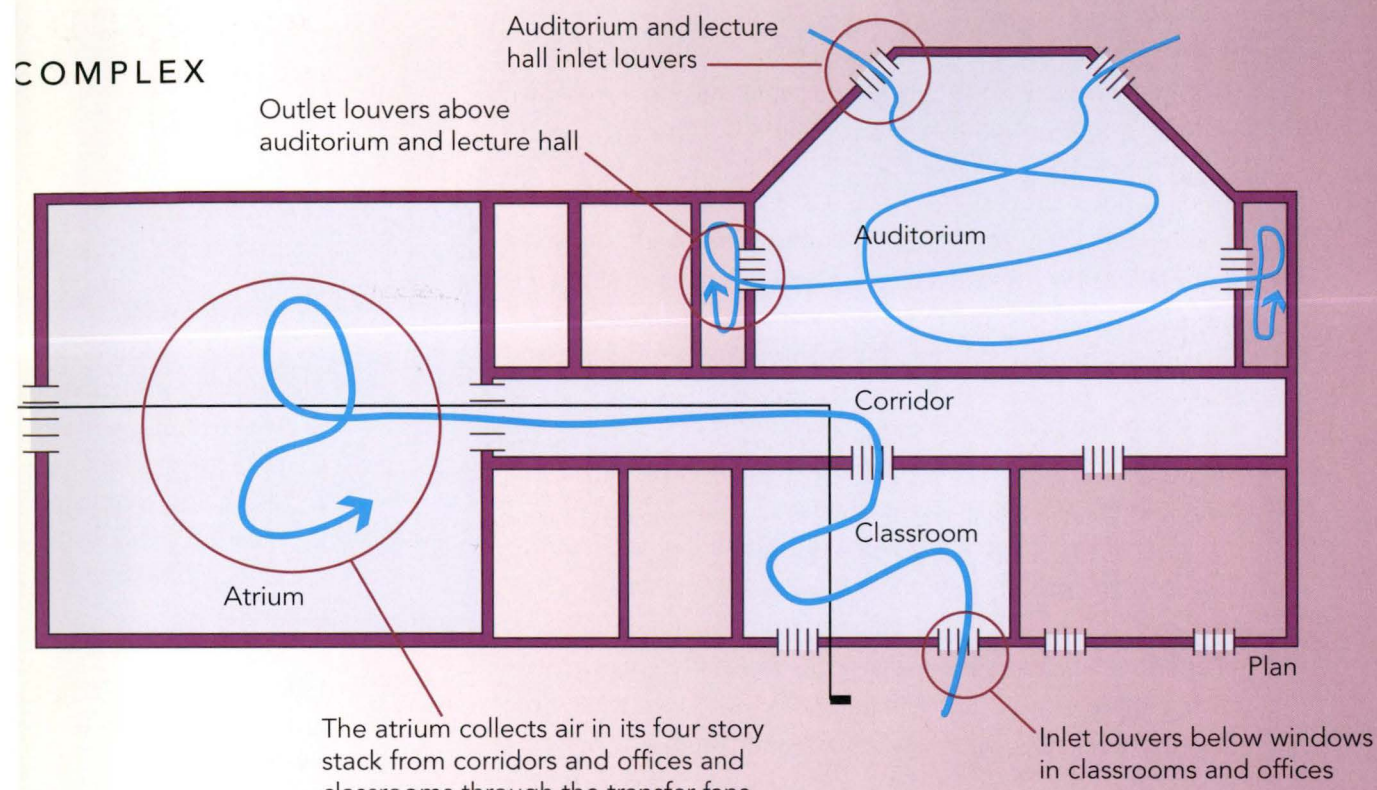
Won't natural ventilation create drafts that make people uncomfortable and blow papers around?

- Prolonged exposure to uncomfortably high temperatures, noise, or air pollutants such as pollen does reduce productivity.
 - However, there is evidence that people's expectations for temperature in naturally ventilated buildings are different from those for mechanically cooled spaces. So while there are definite limits to the comfort zone, they can be higher for people in naturally ventilated buildings.
 - Outside air pollutants such as pollen are seasonal and affect only a small percentage of the population. Since the problem is intermittent and not all people are affected, certain spaces can be filtered by the mechanical system and be occupied by pollen sufferers, and other spaces can be naturally ventilated. This strategy was used for faculty offices in the recently completed Lillis Business School, where one-half of the faculty offices are mechanically cooled and one-half use natural ventilation. In addition, it may be possible to night ventilate a building to cool its mass as long as the next day the outside air is filtered by the mechanical system.
 - Natural ventilation during the day can create acoustic problems by admitting outdoor sounds or preventing acoustic isolation between rooms. However, acoustic isolation can be achieved by ventilating separate acoustic zones with individual stacks, and outside noise can be muted by using sound-baffled inlets and by careful design and location of openings.
- 
- During the heating season outside air ventilation can make people near the inlets feel uncomfortable, especially in climates on the east side of the Cascades. To mitigate this problem, outside air can be tempered with exhaust air heat recovery or run across heating coils at the building perimeter before it gets to the occupants. Because the outside air requirements are small for most rooms, if the openings are designed so that good mixing occurs before the air reaches people, there is less draft potential. In warmer months air movement across the body makes people feel cooler and is usually beneficial.

CASE STUDY LILLIS BUSINESS

Drawings and photographs
are by the Energy Studies in
Buildings Laboratory

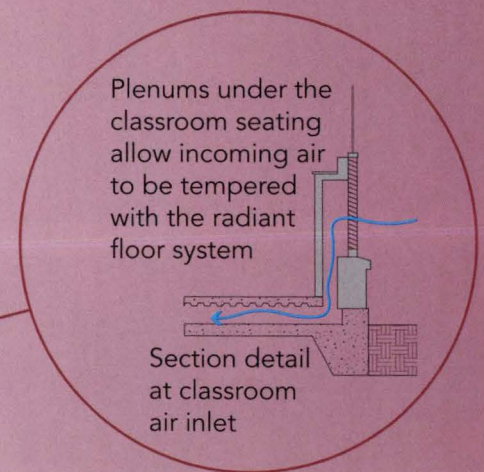
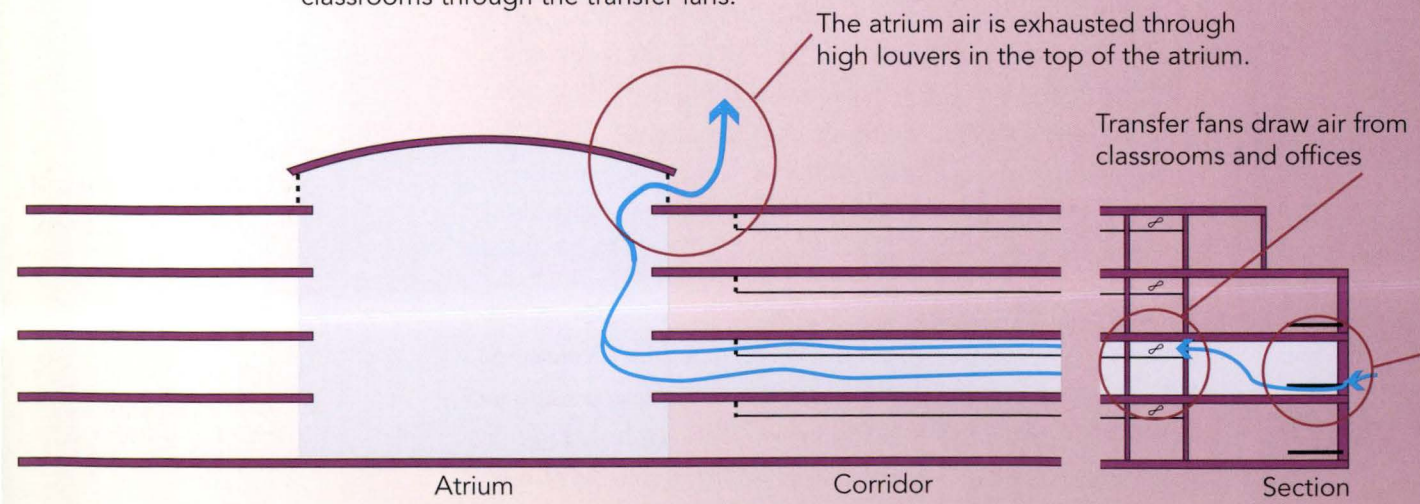
COMPLEX



The north exterior offices have a system to supply minimum outside air, people cooling, and space cooling without going through the HVAC system. Dampers and the transfer fan speed are automatically set by the building control system. Ceiling fans are used to cool people.

Stack ventilation is used in the atrium to exhaust air used for outside air and cooling people, spaces, and mass. A building HVAC fan can be used to mechanically exhaust the atrium if the gravity ventilators are not keeping up with the demand. The stack ventilation dampers and the HVAC system are linked together through the building control system so that one or the other is operating but not both.

Location: University of Oregon
Owner: University of Oregon
Architect: SRG Partnership, Inc.
Mechanical, Electrical, & Civil Engineers: Balzhiser & Hubbard Engineers
Energy: Hatten/Johnson Associates;
Energy Studies in Buildings Laboratory



Don't fire codes limit the use of natural ventilation in buildings?

- In natural ventilation, pressure differences are small and window areas are large so that, with the exception of cross ventilation on windy days, air movement is usually less than that created by a ceiling fan.



- The same passageways created to naturally ventilate buildings have the potential to supply oxygen to a fire and to permit the fire to spread. The size and type of openings between interior spaces and the exterior permitted by code are a function of a building's occupancy, construction type, active fire protection system, and location on the site.
- Cross ventilation inlets and outlets on the exterior that open to courts, yards, or public ways can be limited in size or not permitted depending on the nearness of other buildings. Most of the restrictions on openings apply when the building is less than 20 feet from a property line or another building, although the restrictions vary depending on the exterior wall size and the character of adjacent building walls. However, adjacent buildings that are within 20 feet can be substantial obstructions to the wind, limiting the effectiveness of cross ventilation for cooling.
- Stack ventilation openings on the exterior have the same restrictions as those for cross ventilation. However, because atriums, malls, shafts, and stairwells play such an important role in creating a stack, the code restrictions on those elements are more important in determining the feasibility of using stack ventilation. When a design already has budgeted stacks that have large doors that are automatically closing fire assemblies, they can be cost-effective outlets for night ventilation of mass.
- The types of cross and stack ventilation openings between rooms and between rooms and corridors vary significantly according to a building's construction type and active fire protection system. The use of exits and exit access corridors as supply or exhaust plenums for mechanical systems is restricted by the mechanical code.

MATHEMATICS

Nomenclature:

∂ : partial derivative

Δ : change in

$\bullet$: dot product

A: area

c.s.: control surface

c.v.: control volume

C_2 : conversion coefficient

C_3 : conversion coefficient

C_4 : conversion coefficient

C_D : discharge coefficient

C_P : pressure coefficient

C_V : velocity coefficient

d: derivative

D: substantial derivative

F: force vector

g: acceleration due to gravity vector

K: coefficient

n: exponential coefficient

n: outward normal unit vector

P: pressure

P_w : pressure due to wind

Q: volumetric flow rate

t: time

U: velocity

v: velocity vector

V: volume

y: rectangular coordinate

μ : viscosity

ρ : density

∇ : gradient

FOR VENTILATION TOOLS

Air flow models are derived from Newton's second law of motion: "The time rate of change of momentum of a system is equal to the net force acting on the system and takes place in the direction of the net force."

$$\sum \mathbf{F} = \iint_{c.s.} \rho \mathbf{v} (\mathbf{v} \cdot \mathbf{n}) dA + \frac{\partial}{\partial t} \iiint_{c.v.} \rho \mathbf{v} dV$$

The Navier-Stokes equations are the differential form of Newton's second law of motion.

$$\rho \frac{D\mathbf{v}}{Dt} = \rho \mathbf{g} - \nabla P + \mu \nabla^2 \mathbf{v}$$

If the flow is inviscid the Navier-Stokes equation becomes Euler's equation.

$$\rho \frac{D\mathbf{v}}{Dt} = \rho \mathbf{g} - \nabla P$$

When Euler's equation is integrated for steady incompressible flow, it becomes Bernoulli's equation.

$$\frac{v^2}{2} + gy + \frac{P}{\rho} = \text{constant}$$

The volumetric flow rate is calculated through a power law with different values for the constant and exponent depending on experimental results or assumptions.

$$Q = K(\Delta P)^n$$

The simplified models are single zone models that modify the Bernoulli equation to fit other variables and corrections since case specific data is not usually available. For example, the opening area is modified for entrance effects. With cross ventilation, the velocity of the opening is replaced with wind speed at a different location and then adjustments are made to try to determine the velocity through the opening. An example of how these terms show up in different models is how ASHRAE Fundamentals shows the flow through large openings as:

$$Q = C_3 C_D A \sqrt{\frac{2\Delta P}{\rho}}$$

which has the power law form:

$$Q = K(\Delta P)^n$$

ASHRAE Fundamentals lists the pressure due to wind as:

$$P_w = C_2 C_P \rho \frac{U^2}{2}$$

which has Bernoulli equation form:

$$\frac{v^2}{2} + gy + \frac{P}{\rho} = \text{constant}$$

if you plug wind pressure into flow:

$$Q = C_3 C_D A \sqrt{\frac{2C_2 C_P \rho U^2}{2\rho}}$$

and simplify:

$$Q = C_3 C_D \sqrt{C_2 C_P} AU$$

which has the same form as ASHRAE:

$$Q = C_4 C_v AU$$

of unit conversions, a flow correction factor, area and velocity.

In stack ventilation the density of the air in the stack is replaced with a temperature variable. Unlike the single zone simplified models, network and zonal models subdivide architectural spaces into increasingly smaller zones. Computational fluid dynamics (CFD) models have the capability to further subdivide the space in order to predict the flow patterns and velocities. CFD models use the Navier-Stokes equation directly.

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