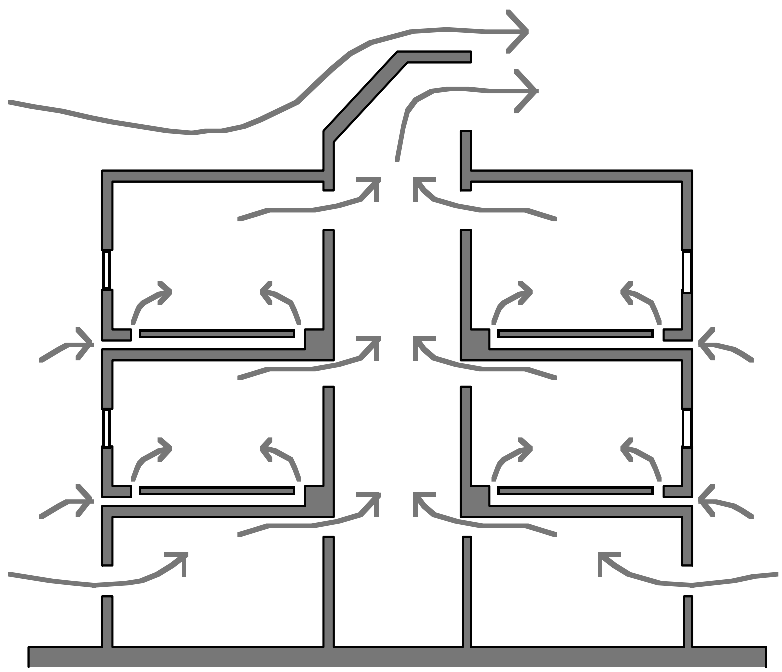
CALIFORNIA ENERGY COMMISSION

Final Report Compilation for

Design Methods and Guidelines for Natural Ventilation



Global Stack Ventilation w/ Sub-slab Distribution

TECHNICAL REPORT

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Gray Davis, *Governor*

CALIFORNIA ENERGY COMMISSION

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The Program's final report and its attachments are intended to provide a complete record of the objectives, methods, findings and accomplishments of the Energy Efficient and Affordable Commercial and Residential Buildings Program. This attachment is a compilation of reports from Project 4.4, *Design Methods and Guidelines for Natural Ventilation*, providing supplemental information to the final report (Commission publication #P500-03-096). The reports, and particularly the attachments, are highly applicable to architects, designers, contractors, building owners and operators, manufacturers, researchers, and the energy efficiency community.

This document is one of 17 technical attachments to the final report, consolidating three research reports from Project 4.4:

- *Natural Ventilation Review and Plan for Design and Analysis Tools (NISTIR 6781)* (Aug 2001)
- *LoopDA – A Natural Ventilation System Design and Analysis Software Manual* (Aug 2003)
- *Impact of Natural Ventilation and Design Issues for California Applications, Including Input to ASHRAE Standard 62 and California Title 24* (Sep 2003)

LoopDA, Natural Ventilation Loop Design Assistance Software, can be downloaded from the following web site:

http://www.bfrl.nist.gov/IAQanalysis/LOOPDAdesc.htm

The Buildings Program Area within the Public Interest Energy Research (PIER) Program produced this document as part of a multi-project programmatic contract (#400-99-011). The Buildings Program includes new and existing buildings in both the residential and the nonresidential sectors. The program seeks to decrease building energy use through research that will develop or improve energy-efficient technologies, strategies, tools, and building performance evaluation methods.

For the final report, other attachments or reports produced within this contract, or to obtain more information on the PIER Program, please visit www.energy.ca.gov/pier/buildings or contact the Commission's Publications Unit at 916-654-5200. The reports and attachments, as well as the individual research reports, are also available at www.archenergy.com.

Abstract

Project 4.4, *Design Methods and Guidelines for Natural Ventilation*

These NIST project objectives included developing natural ventilation design strategies and design methods for small commercial buildings, addressing the impact of outdoor air quality on natural ventilation, and developing natural ventilation software tools.

- A new ventilation cooling metric was described and used to demonstrate that the coastal climates of California are potentially very well suited to natural ventilation.
- The hotter, inland locations are less suited to a simple natural ventilation strategy but may be able to benefit from night cooling or hybrid system strategies.
- An eight-step design approach for natural ventilation applications was developed.
- A review of ambient air quality data indicated that much of California fails to meet the national standards for one or more contaminant. However, since ambient air quality problems may vary by season, time-of-day, and locality, natural ventilation strategies may still be considered acceptable at all times in some areas and part of the time in other areas through innovative hybrid systems.
- Natural ventilation design and analysis software, called LoopDA (for Loop Design and Analysis), was developed to aid in sizing and placement of natural ventilation devices. LoopDA is based on CONTAMW 2.0, a multi-zone airflow model.

This document is a compilation of three technical reports from the research. The LoopDA software is available from NIST.

NISTIR 6781

Natural Ventilation Review and Plan for Design and Analysis Tools

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NIST

National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

NISTIR 6781

Natural Ventilation Review and Plan for Design and Analysis Tools

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ABSTRACT

Natural ventilation has the potential to reduce first costs and operating costs for some commercial buildings while maintaining ventilation rates consistent with acceptable indoor air quality. While a recent surge of interest in Europe has advanced natural ventilation technology, much work is needed before this potential can be realized in the U.S. This report reviews the application of natural ventilation in commercial buildings, the technology, its potential advantages and related issues that need to be addressed. One area identified as a key to the realization of the potential advantages of natural ventilation is the emergence of hybrid natural and mechanical system strategies. The report also addresses opportunities and issues specific to the application of natural ventilation to commercial buildings in California including analysis of climate suitability via a new ventilative cooling metric, consideration of ambient air quality, and discussion of relevant codes and standards. Finally, current design and analysis processes and tools are reviewed, and a plan for the development of new design and analysis guidance and tools is described.

Keywords: analysis, design, energy efficiency, indoor air quality, modeling, natural ventilation, ventilation

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1. Introduction

Natural ventilation has the potential to significantly reduce the energy cost required for mechanical ventilation of buildings. These natural ventilation systems may reduce both first and operating costs compared to mechanical ventilation systems while maintaining ventilation rates that are consistent with acceptable indoor air quality. Also, some studies have indicated that occupants reported fewer symptoms in buildings with natural ventilation compared to buildings with mechanical ventilation [Mendell et al. 1996]. If natural ventilation can improve indoor environmental conditions, such improvements can also potentially increase occupant productivity by reducing absenteeism, reducing health care costs, and improving worker productivity [Fisk and Rosenfeld 1997].

Because of these potential benefits, natural ventilation is being increasingly proposed as a means of saving energy and improving indoor air quality within commercial buildings, particularly in the "green buildings" community. These proposals are often made without any engineering analysis to support the claimed advantages, e.g., without calculating expected ventilation rates or air distribution patterns. In addition, proven design approaches are not available in this country to incorporate natural ventilation into commercial building system designs. Natural ventilation strategies are less likely to reach the U.S. marketplace until design tools are made available and strategies are investigated and demonstrated for a variety of climates and construction types.

While natural ventilation is becoming more common in Europe, significant questions exist concerning its application in U.S. commercial buildings. These questions include the reliability of the outdoor air ventilation rates, distribution of this outdoor air within the building, control of moisture in naturally ventilated buildings, building pressurization concerns, and the entry of polluted air from outdoors without an opportunity to filter or clean it. Some climates within California may be well suited to natural ventilation, but these questions still must be addressed for these locales. The NIST multi-zone airflow and indoor air quality (IAQ) analysis model, CONTAMW [Dols et al. 2000], is capable of addressing many of these and other issues related to natural ventilation in buildings. In addition, the airflow calculation capabilities of CONTAMW can serve as the basis of a natural ventilation design tool, enabling wider use of natural ventilation in a technically sound manner.

This report presents the results of the first phase of a project intended to investigate the application of current natural ventilation concepts in commercial buildings in California and to develop design methods for natural ventilation in new and retrofit applications. This project will:

- Develop natural ventilation strategies for cooling load reduction in commercial buildings in California.
- Develop natural ventilation design methods, construction techniques, and strategies that address non-energy issues, such as occupant comfort, air filtration, and acoustical isolation.
- Assess indoor air quality impacts of natural ventilation in commercial buildings.
- Develop natural ventilation software tools for design to improve building energy efficiency and lower the cost of building design, construction, and operation.

This report is organized into three main sections – Review of Natural Ventilation Technology, California Opportunities and Issues, and Design and Analysis Tools. The first section contains an overview of natural ventilation in commercial buildings and its potential advantages and a discussion of issues that need to be addressed. It also describes state-of-the-art natural ventilation technologies and strategies available to maximize the performance of natural ventilation systems. The second section discusses opportunities and issues specific to the application of natural ventilation systems to small commercial buildings in California. The third section reviews currently available natural ventilation system design and analysis tools and describes a plan to provide tools to enable the realization of the potential benefits of natural ventilation systems in California. Note that some material in this report is extracted from Axley [2001b] and is not individually referenced.

2. Review of Natural Ventilation Technology

This section gives an overview of natural ventilation in commercial buildings and its potential advantages and issues to overcome. It also describes state-of-the-art natural ventilation technologies and strategies available to maximize the performance of natural ventilation systems.

2.1 Introduction to Natural Ventilation

Ventilation, whether mechanical or natural, may be used for:

- *Air Quality Control:* to control building air quality, by diluting internally-generated air contaminants with cleaner outdoor air,
- *Direct Advective Cooling:* to directly cool building interiors by replacing or diluting warm indoor air with cooler outdoor air when conditions are favorable,
- *Direct Personal Cooling:* to directly cool building occupants by directing cool outdoor air over building occupants at sufficient velocity to enhance convective transport of heat and moisture from the occupants, and
- *Indirect Night Cooling:* to indirectly cool building interiors by pre-cooling thermally massive components of the building fabric or a thermal storage system with cool nighttime outdoor air.

While these four distinct purposes must be kept in mind when designing a natural ventilation system, direct advective and personal cooling are reasonably achieved in an integrated manner by a properly designed *direct cooling* strategy. Consequently, just three purposes are most often noted in the literature – air quality control, direct cooling, and indirect cooling.

Natural ventilation may be defined as ventilation provided by thermal, wind or diffusion effects through doors, windows, or other intentional openings in the building as opposed to mechanical ventilation that is ventilation provided by mechanically powered equipment such as motor-driven fans and blowers. Although some in the U.S. may think of natural ventilation as simply meaning operable windows, natural ventilation technology has been advanced in recent years in Europe and elsewhere.

The variety and diversity of purpose-provided natural ventilations systems that have been proposed in recent years is staggering [Allard 1998, BRE 1999, CIBSE 1997, Martin 1995]. Hybrid variations of many of these systems, wherein mechanical devices are added to enhance system performance and control, add yet another level of complication. Nevertheless, these systems are invariably conceived as variants of three fundamental approaches to natural ventilation:

- Wind-driven cross ventilation
- Buoyancy-driven stack ventilation, and
- Single-sided ventilation.

<u>Wind-Driven Cross Ventilation</u>

Wind-driven cross ventilation occurs via ventilation openings on opposite sides of an enclosed space. Figure 1 shows a schematic of cross ventilation serving a multi-room building, referred to here as global cross ventilation. The building floorplan depth in the direction of the ventilation flow must be limited to effectively remove heat and pollutants from the space by typical driving forces. A significant difference in wind pressure between the inlet and outlet openings and a minimal internal resistance to flow are needed to ensure sufficient ventilation flow. The ventilation openings are typically windows.

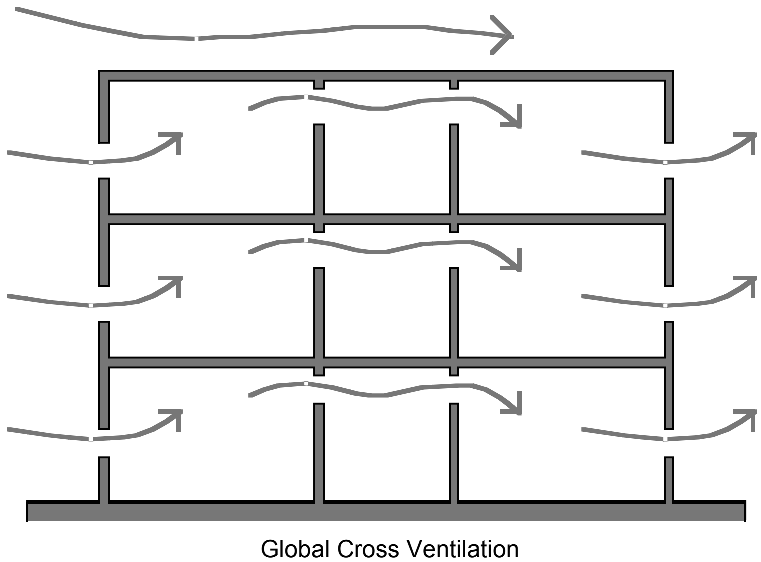

Figure 1 Schematic of wind-driven cross ventilation

<u>Buoyancy-Driven Stack Ventilation</u>

Buoyancy-driven stack ventilation relies on density differences to draw cool, outdoor air in at low ventilation openings and exhaust warm, indoor air at higher ventilation openings. Figure 2 shows a schematic of stack ventilation for a multi-room building. A chimney or atrium is frequently used to generate sufficient buoyancy forces to achieve the needed flow. However, even the smallest wind will induce pressure distributions on the building envelope that will also act to drive airflow. Indeed, wind effects may well be more important than buoyancy effects in stack ventilation schemes, thus the successful design will seek ways to make full advantage of both.

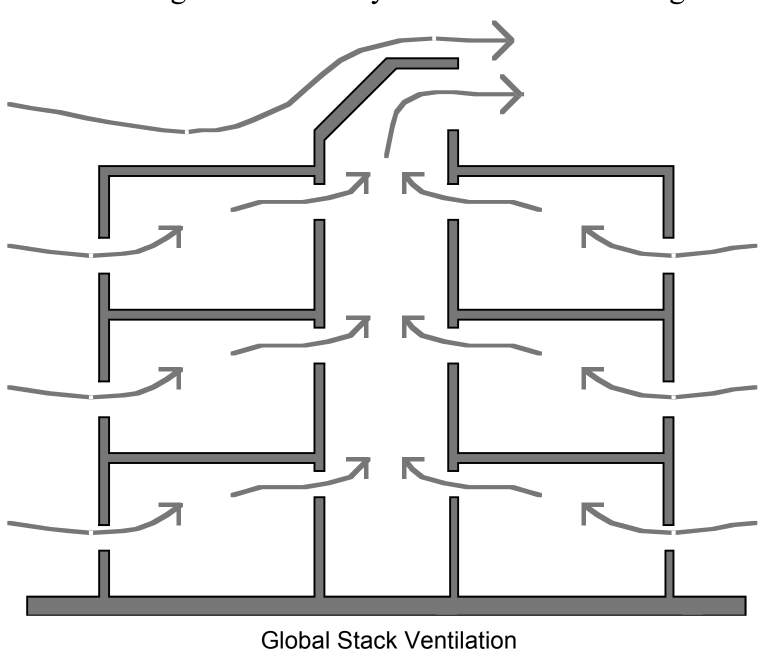

Figure 2 Buoyancy-driven stack ventilation

Single-Sided Ventilation

Single-sided ventilation typically serves single rooms and thus provides a local ventilation solution. Figure 3 shows a schematic of single-sided ventilation in a multi-room building. Ventilation airflow in this case is driven by room-scale buoyancy effects, small differences in envelope wind pressures, and/or turbulence. Consequently, driving forces for single-sided ventilation tend to be relatively small and highly variable. Compared to the other alternatives, single-sided ventilation offers the least attractive natural ventilation solution but, nevertheless, a solution that can serve individual offices.

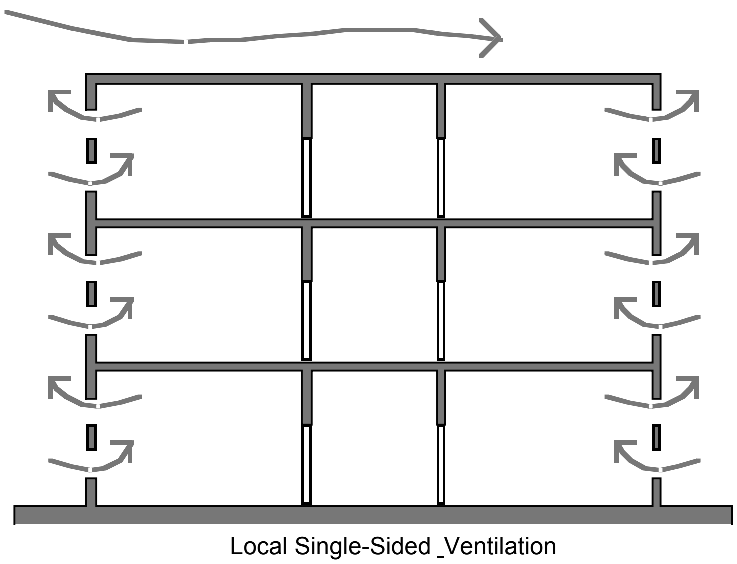

Figure 3 Schematic of single-sided ventilation

Elaborations of the Basic Strategies

Many built examples employ elaborations of these basic schemes. In some instances these three schemes have been used in a mixed manner in single buildings to handle a variety of ventilation needs. The most notable example of such an approach is the Queens Building of De Montfort University in Leichester, England that has proven, perhaps, to be the most influential of the *first generation* of the newer naturally-ventilated buildings. See Figure 4 for a schematic of mixed local/global and stack/wind ventilation strategy.

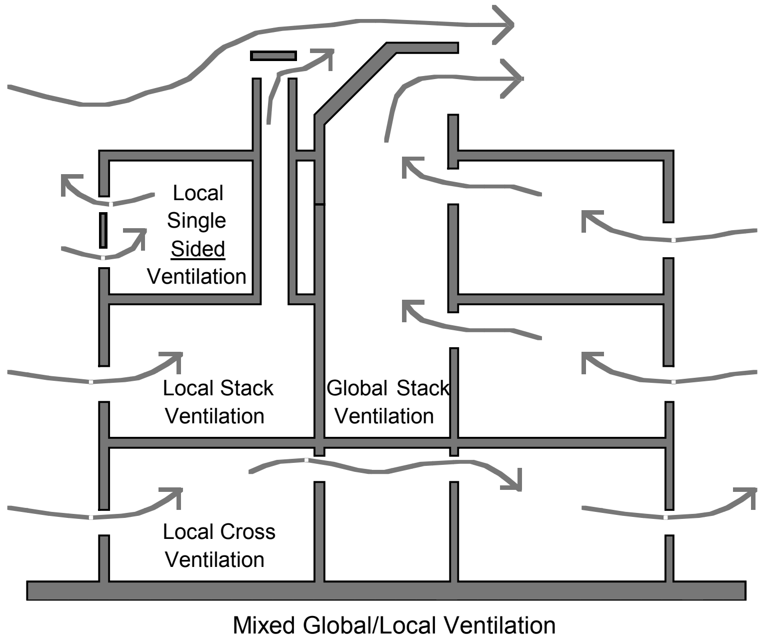

Figure 4 Schematic of mixed natural ventilation strategies

In other instances, the elaboration resides in the details of inlet, exhaust, and distribution tactics. One common approach involves the use of in-slab or access-floor distribution of fresh air to provide greater control of air distribution across the building section. Figure 5 shows a schematic of stack ventilation with a sub-slab distribution system.

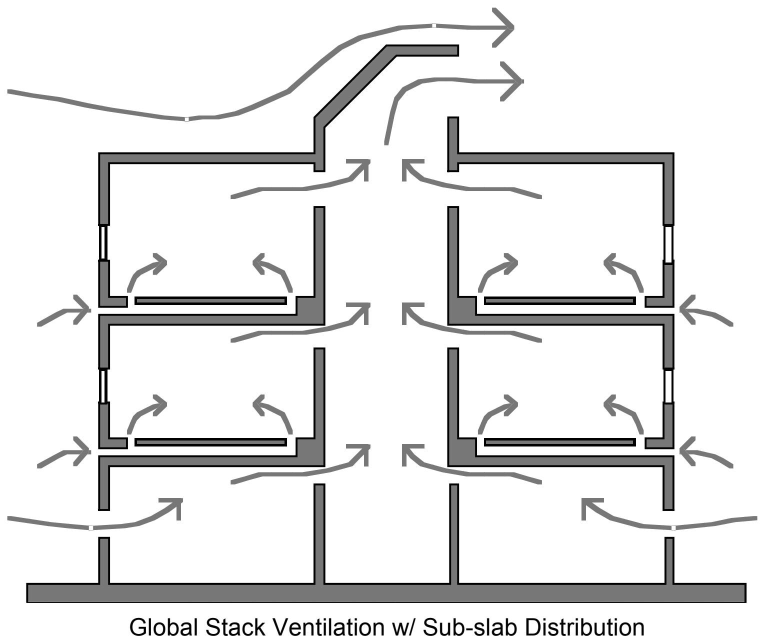

Figure 5 Schematic of stack ventilation with sub-slab distribution

The CIBSE Applications Manual [CIBSE 1997] and Martin [1995] describe dozens of natural ventilation cases (seven in detail) applying modern natural ventilation technology incorporating advanced windows, trickle ventilators, window and vent actuators, thermal chimneys, wind chimneys, dampers, thermal mass, and atria. The case study buildings are typically six stories or fewer and are used for office, education, retail, and industrial purposes.

2.2 Pros and Cons of Natural versus Mechanical Ventilation

A number of issues should reasonably be considered when comparing natural ventilation strategies to mechanical alternatives. Here, sets of these issues that are inextricably linked will be considered including a) cooling energy savings and limits of applicability, b) fan power savings and heat recovery, c) control and reliability, d) occupant health, comfort and productivity, e) HVAC equipment costs and space requirements, f) duct cleanliness and filtration, and g) other issues such as acoustical isolation, privacy, security, etc.

Cooling Energy Savings and Limits of Applicability

When applicable, natural ventilation can offset cooling energy consumption and the associated energy costs and carbon dioxide emissions thought to be related to global climate changes. In direct comparisons of naturally ventilated and air-conditioned offices in the United Kingdom, naturally ventilated buildings offset from 14 kWh/m^2 to 41 kWh/m^2 of cooling energy annually, for *good practice standard* office buildings to *typical prestige* office buildings respectively, saving from 0.77 £/m^2 to 2.05 £/m^2 (approximately 1.30 \$/m^2 (0.12 \$/ft^2) to 3.60 \$/m^2 (0.33 \$/ft^2)) annually in energy costs [BRECSU 2000]. These savings account for approximately 10 % of total energy costs in a climate where outdoor air temperatures seldom exceed thermal comfort limits in the summer and thus, one well-suited for ventilative cooling of office buildings.

The potential cooling energy that may be saved depends, of course, on both the climate in which a building is located and the relative level of internal and other gains that impact the building's thermal performance. Clearly, when natural ventilation is not applicable due either to outdoor temperatures or, in some instances, outdoor humidities that are too high, then these energy savings cannot be realized. The general question of climatic suitability will be addressed in a subsequent section of this report and methods presented to evaluate the limits of applicability of ventilative cooling strategies.

Fan Power & Heat Recovery

Of course, ventilative cooling may be accomplished by either natural means or mechanical means (e.g., using so-called *economizer cycle* operation). When resorting to mechanical means to cool buildings, however, fans will consume a significant amount of the energy. In all-air systems – the most common mechanical system cooling strategy in the U.S. – fans consume at least two-thirds of the total energy consumed for cooling in office buildings in the United Kingdom [BRECSU 2000]. While a directly comparable number is not readily available for the U.S., there is a growing awareness that fans consume a large portion of the energy used to cool buildings [Brodrick and Westphalen 2001]. When compared to all-air mechanical cooling systems, naturally ventilated buildings in the U.K. offset from 20 kWh/m^2 to 60 kWh/m^2 of fan energy consumption annually for cooling purposes, saving from 1.0 £/m^2 to 3.0 £/m^2 (approximately 1.70 \$/m^2 (0.16 \$/ft^2) to 5.20 \$/m^2 (0.48 \$/ft^2)) annually in energy costs (i.e., again for *good practice standard* to *typical prestige* office buildings). By implication, these savings account for approximately 15 % of total energy consumption in U.K. office buildings.

These statistics from the U.K. establish the potential that natural ventilation offers when climatic and operational conditions prove particularly suitable. Roughly, natural ventilation may be expected to provide cooling energy savings on the order of 10 % and fan power savings (i.e., for all-air systems) on the order of 15 % of annual energy consumption when climatic and operational conditions are suitable.

U.S. statistics to support these U.K. observations are a bit sparse but are available. Kavanaugh [2000] reports that as mechanical cooling systems have become increasingly complex in the U.S. the relative importance of fan power energy consumption has increased:

> "The good news is that chillers, furnaces, compressors, and other HVAC components are becoming increasingly efficient. The bad news is that air system friction losses, high ventilation rates, filter efficiency requirements, part-load air distribution methods, and the lack of space for ductwork can combine to make fan demand and energy the largest component in HVAC systems. ..."

Kavanaugh investigated three systems – two centralized air handling systems with variable air volume (VAV) air distribution systems and a distributed system with multiple fan coil units (FCU). Full-load energy consumption was estimated for each of these three options indicating fans accounted for 53 % of energy consumption in the more common relatively high pressure VAV system, 36 % for a low-pressure VAV system, and 24 % for the very-low-pressure distributed FCU system. The reduced fan power consumption realized by the lower pressure systems, however, was offset in part by increased chilled water pumping costs resulting in the combined fan and pump energy costs ranging from 40 % to 62 %. For part-load demand an additional significant penalty is paid in losses of fan efficiency [Kavanaugh 2000]. Combined together, then, Kavanaugh's analysis supports the U.K. findings that in conventional all-air systems, fans account for approximately two-thirds of the total energy consumed for cooling. The less common low-pressure mechanical systems, however, mitigate the impact of these *parasitic losses*.

Heat recovery, on the other hand, is put forward as the key advantage of mechanical ventilation systems – the demonstrated advantage of a number of mechanical system configurations to recover thermal energy from exhaust air through the use of air-to-air and so-called "run-around" air-to-water-to-air heat exchangers. Indeed in the cold climate of Finland it has been estimated that fan-power accounts for only 13 % of annual energy consumed in ventilating buildings while the remaining 87 % is used to condition, specifically in Finland to heat, the ventilating air [Heikkinen and Heimonen 2000]. Even a modest heat recovery efficiency could, therefore, have a significant impact during the heating season in cold climates.

The potential benefit of heat recovery during the cooling season is likely, however, to be marginal. This is due, in part, to the relatively small temperature difference between outdoor and indoor air during even extreme summer conditions in most of the U.S. and, in part, due to additional parasitic energy consumption required by fans in mechanical heat recovery systems. Indeed, Kavanaugh presents an analysis of one office building equipped with a heat recovery unit (HRU) following manufacturer's recommendations in Birmingham, Alabama and concludes: "Annual energy savings with the HRU were non-existent due to the large amount of fan power energy consumed." However, one may better realize the benefits of HRUs if these units are designed to minimize pressure losses when significant heat recovery may be affected and to bypass them under other operating conditions [Berry 2000].

Nevertheless, if natural ventilation strategies are to be competitive during extreme seasons, when either mechanical heating or cooling must be provided, then they may need to be designed to recover heat. This has become a central goal of the most recent work in the development of natural ventilation systems and thus will be considered below. Conversely, however, it must be emphasized that during the shoulder seasons, when mechanical heating or cooling need not be provided, heat recovery is no longer an issue; thus, the fan power savings offered by natural ventilation systems stands unqualified.

Likewise, as mechanical systems have been devised that more effectively recover heat then the relative importance of the fan-power consumed in these systems becomes more significant. Consequently, recent research on the mechanical side has been directed to the development of low-pressure mechanical systems in an effort to minimize fan-power consumption [Heiselberg 2000]. Depending on the system design, low-pressure mechanical systems may have a building owner cost in building space.

Control and Reliability

In mechanical ventilation systems, fans that are often controlled electronically drive airflow. On the other hand, wind and buoyancy forces that are stochastic in nature drive natural ventilation, making control more difficult. As a result natural ventilation systems may at times *under-ventilate*, resulting in overheating or unacceptable air quality conditions, *over-ventilate*, resulting in unnecessary energy consumption to condition indoor air, or provide *unacceptable air distribution*, resulting in local thermal discomfort due to cold drafts or insufficient cooling or local air quality problems.

At face value, the control and reliability offered by mechanical ventilation systems would appear to be a significant advantage when compared to natural ventilation systems. Indeed, this is often cited as the primary reason mechanical ventilation should be preferred to natural. However, in practice, mechanical ventilation systems are often regulated to control temperature rather than air quality and, thus, may not provide adequate ventilation for air quality control. For example, VAV systems, which are commonly used in commercial buildings, may fail to maintain acceptable air quality for this reason [Leyten and Kurvers 2000]. On the other hand, mechanical ventilation systems that are controlled based on indoor contaminant levels, while not commonly used in practice, have the potential to be both reliable and energy efficient in operation.

The need to maintain ventilation rates reliably and the inherent difficulty of doing so when using natural driving forces must be seen as a major challenge for the development of natural ventilation systems. Consequently recent research efforts have been directed to meet this challenge. System design strategies, including axisymmetric exhaust vents and inlet vents linked via a common plenum space, have been identified that reduce sensitivity to wind direction and thus improve the directional reliability of wind-driven flow. Recently developed automatic, self-regulating vents [Knoll and Kornaat 1991; Anon 1992; Knoll 1992; de Gids 1997; de Gids 1999] and digital control strategies coupled to controlled inlet devices [Knoll and Phaff 1998] may provide the means to control over-ventilation and the associated discomfort due to cold drafts. As promising as these recent developments are, however, purely natural ventilation systems will fail when the natural driving forces are simply not available, consequently recent trends have favored fan-assisted natural ventilation.

Occupant Health, Comfort & Productivity

The actual health, comfort, and productivity impacts of mechanical ventilation systems often fall short of expectations [Fisk and Rosenfeld 1997; Fisk 1998]. In comparisons of negative health symptoms of office workers in a limited number of naturally and mechanically ventilated systems, in both the European and North American context, the naturally ventilated buildings reported lower symptom prevalence in comparison to the mechanically ventilated and, especially, air conditioned buildings [Mendell et al. 1996]. Much anecdotal evidence supports these scientific findings, yet the fundamental reasons behind these findings are not self-evident.

A recent Dutch study supports these findings and attempts to explain why they are observed:

> "Epidemiological studies consistently show that occupants' complaints are more prevalent in office buildings with more sophisticated HVAC systems, that is systems with more technological devices to control and regulate the indoor environment. These complaints not only include physical symptoms, but also complaints about indoor air quality and thermal comfort. Since in most cases these more sophisticated systems primarily aim at better compliance with some set of health and comfort standards, the higher complaint levels seem odd. The most frequent explanation of this phenomenon is that more sophisticated HVAC systems contain more potential sources of indoor air pollution, like filter sections, cooling sections and humidifiers. The authors of this paper submit that this, though in itself correct, is only part of the explanation, and that a more comprehensive explanation can be hypothesized." [Leyten and Kurvers 2000]

Leyten and Kurvers go on to introduce the notion of system *robustness* – the ability of a system to perform up to expectations when assumptions and conditions underlying its design are violated. They offer a number of reasons HVAC systems may lack robustness: systems may be particularly sensitive to "aberrations" in their underlying design assumptions, maintenance requirements of systems may not be feasible or simply not addressed, integration of heating (or cooling) and ventilation places conflicting demands on system operation and control, systems sensitive to the regulation of airflow rates (especially recirculation airflow rates) may not be feasible, and difficulty in understanding system operation on the part of both occupants and building operators. In short, they conclude that the more complex, "sophisticated," HVAC systems tend to be less robust than the simpler, more comprehensible systems. Importantly they conclude that natural ventilation systems tend to rank high in terms of robustness [Leyten and Kurvers 2000]. While the concept of robustness may be behind the differing symptom rates in mechanically and naturally ventilated buildings, additional studies are needed to support this explanation.

The growing importance of adaptation in thermal comfort considerations [Nicol and Raja 1997; Olesen 2000] may well be linked to Leyten and Kurvers' identification of system legibility or *transparency* as a prerequisite of robustness. If a system is *transparent* to the occupants of the building the occupants can act directly to identify the causes of problems that compromise health, comfort, and even productivity. If, in addition, occupants are offered control of these systems they will make changes to mitigate these problems. This has led to the conclusion that natural ventilation systems that offer occupant control over ventilation rates (and solar gain) can be effectively designed for slightly larger comfort zones than commonly used in the design of mechanical HVAC systems [Conte and Fato 2000; Martinez, Fiala et al. 2000; Brager and de Gear 2000]. Indeed, a recent study of a school whose mechanical system was replaced by a natural ventilation system offering user control concluded [Gunnarsen 2000]: "The school users were as good, or better, at obtaining comfortable temperature and air quality as the poorly maintained mechanical ventilation system with central automation."

While it is tempting to conclude from these limited studies that natural ventilation systems can provide more healthful, comfortable, and productive environments, it may be more reasonable to conclude that *robust* natural ventilation systems may offer this advantage. There is a trend in the design of natural ventilation systems in recent years towards complexity – these complex natural ventilation systems may well prove to be less robust and thus may suffer shortcomings similar to those of the more complex mechanical ventilation systems.

Beyond quantitative evaluations of health, comfort, and productivity advantages that natural ventilation systems may offer, it is important to recognize that many if not most building occupants may simply prefer natural ventilation systems qualitatively. Largely for these reasons alone, architects have accepted natural ventilation as one of several objectives of high quality sustainable design.

HVAC Equipment Cost & Space Requirements

Mechanical heating, ventilating, and air conditioning equipment often account for a large fraction of the cost of construction of new buildings and the renovation of existing buildings. In larger office and institutional buildings, these costs may be expected to range from 35 % to 45 % of construction costs. Consequently, the first cost savings that may be realized by replacing, or at least reducing, mechanical systems for ventilation and cooling by natural ventilation systems is, potentially, quite large.

Yet first cost savings represent only part of the advantage that may be offered by natural ventilation. Mechanical air handling equipment including fans, filters, heating and cooling coils, vertical distribution shafts and ducts, horizontal distribution duct networks, dampers, reheat or VAV boxes and the like, and supply diffusers and return grilles consume vast amounts of space. In larger commercial buildings with conventional all-air systems, an enclosed ceiling space from 0.66 m to 1.32 m (2 ft to 4 ft) high, typically, will be required for the horizontal distribution system components alone – i.e., 0.66 cubic meter per square meter to 1.32 cubic meter per square meter (2 cubic feet per square foot to 4 cubic feet per square foot) of useful floor area. Vertical shaft areas usually range from 1 square meter per 1,000 square meters to 2 square meters per 1,000 square meters (1 square foot per 1,000 square feet to 2 square feet per 1,000 square feet) of floor area served while fan rooms require from 2 % to 4 % of this floor area – together totaling 0.08 cubic meter per square meter to 0.16 cubic meter per square meter (0.25 cubic foot per square foot to 0.50 cubic foot per square foot) of useful floor area [Bradshaw 1993]. For the common commercial building ceiling height of 3.6 m (12 ft), the combined requirements of fans, vertical distribution, and horizontal distribution systems will, therefore, consume 20 % to 40 % of the total volume of the building.

Innovative natural ventilation system designs recover much of this volume as occupiable space by configuring the spatial interior of the building to serve, in essence, as part of the natural ventilation airflow pathway. Not only is space (volume) recovered that may serve more formal architectural objectives, this space may serve to facilitate daylight distribution, by increasing the height to depth of room sections, and to mitigate rapid increases in indoor air pollutants by simply increasing the total volume of air hence contaminant capacity contained within rooms. Alternatively, the space recovered may be used to reduce the total floor-to-floor height in multistory construction to either effect a savings in the cost of building construction or to allow the inclusion of one or more additional floors – and thus the income generated from their rent or sale – within a given urban building height limitation. Note that other innovative systems may also recover building space compared to typical all-air systems.

Duct Cleanliness & Filtration

The spatial, daylighting, air quality, and construction savings benefits that may result from the removal of mechanical air handling systems could, conceivably, exceed the first cost savings offered by replacement of these mechanical systems with natural alternatives. Yet another advantage must also be acknowledged. It is now widely recognized that duct cleanliness and building air quality are intimately linked [Limb 2000] – indeed, it is claimed that ductwork may be a principle source of indoor odors even in new construction [Säateri 1998]. As a result, an entirely new industry has been formed to clean existing ductwork – a potentially difficult and expensive undertaking – and guidelines and standards have been and are being formulated to address this problem [NADCA 1992; NAIMA 1993; ASHRAE 2000; Limb 2000].

Many natural ventilation systems circumvent this problem altogether by, in essence, replacing ductwork with habitable spaces that serve to direct naturally-driven airflows. The routine cleaning and maintenance of these spaces and the ease with which their cleanliness may be inspected provide an inexpensive solution to the general problem of cleaning ventilation airflow paths. On the other hand, natural ventilation systems that admit outdoor air without filtration – still the most common situation in most natural ventilation systems – can, in those urban environments where outdoor dust levels are excessive, result in increased building cleaning and maintenance costs and the annoyance associated with working in a environment with excessive dust and particle loads. (Issues related to outdoor air quality in California are discussed further later in this report.) Consequently, mechanical ventilation systems offer the significant advantage of air filtration but with potential cost and health penalties of unclean ducts while natural ventilation systems, as commonly configured, avoid the duct cleaning problem altogether yet provide little or no filtration of ventilation airflows. Again, it should come as no surprise that research to address these problems is currently underway.

<u>Other Issues</u>

A number of other related issues must be considered when evaluating the potential of natural and/or hybrid ventilation systems including daylighting, acoustical isolation, smoke control and management, rain entrainment, security, and pest control. Of these, the inherent compatibility of daylighting with natural ventilation design strategies is perhaps most significant from an energy point of view. In its survey of U.K. buildings, the Building Research Establishment Conservation Service Unit [BRECSU] data indicate that naturally ventilated buildings typically consume 23 % to 52 % of the energy consumed for artificial lighting in mechanically air conditioned office buildings [BRECSU 2000]. In principle, lighting efficiency should be independent of the ventilation system employed, yet building configurations that serve natural ventilation purposes well are often most appropriate for daylighting strategies that, when applied properly, can significantly offset artificial lighting.

2.3 Future Prospects of Natural Ventilation & the Emergence of Hybrid Strategies

Natural ventilation offers the means to control air quality in buildings, to directly condition indoor air with cooler outdoor air, to indirectly condition indoor air by night cooling of building thermal mass, and to provide refreshing airflow past occupants when desired. While mechanical ventilation systems may also accomplish these goals, natural ventilation systems:

- can offset cooling energy consumption when climate and operational conditions are suitable,
- can offset the fan power required to provide ventilation mechanically,
- potentially provide quantitative health, comfort, and productivity advantages that may, in part, be due to the greater *robustness* of natural ventilation systems,
- provide qualitative advantages of ‘fresh air’ in the minds of most occupants,
- may offer users greater direct control of their environments and, as a consequence, may benefit from less restrictive comfort criteria that results from occupants’ ability to adapt their environment to their immediate perception of comfort,

- can offset a significant fraction of the relatively large first costs associated with conventional mechanical ventilation systems in commercial buildings by simply replacing them with lower cost natural ventilation systems,
- can recover the large spatial requirements that conventional mechanical systems demand and return them to serve formal architectural, daylighting, and air quality objectives or to reduce nonmechanical construction costs, and
- can avoid the duct cleanliness dilemma, and its attendant costs, simply by circumventing the need for ducts altogether.

Yet natural ventilation systems:

- presently lack proven ventilation heat recovery capabilities, although some methods are currently under development,
- are generally difficult to control and are inherently unreliable when natural driving forces are small, and
- presently lack proven filtration capabilities thus may be compromised by environments, particularly urban, with high outdoor particle and gaseous contaminant concentrations.

The potential of natural ventilation systems depends, in part, on the suitability of a given climate, in part, on the design of the natural ventilation system used, and in part, on the advantages offered by mechanical system alternatives. Recent developments in natural ventilation system design have been matched by collateral developments in mechanical ventilation design. Thus, for example, as the development of natural ventilation systems offer a means to ventilate without fan power consumption, research into low pressure ventilation systems answer with mechanical systems with reduced fan power requirements. These and other research developments have led quite naturally to the emergence of so-called *hybrid ventilation systems* that attempt to combine the benefits of both natural and mechanical ventilation in an optimal way [Heiselberg 1999; Heiselberg 2000]. Recent reports of the design and performance of three U.K. buildings clearly indicate the advantages hybrid system may have when compared to both purely natural or purely mechanical ventilation alternatives [Arnold 2000; Braham 2000, Berry 2000]:

> "Independent studies with new buildings using low-energy heat recovery mechanical ventilation integrated into fabric energy storage designs using hollow core slabs have reported better year-round comfort (including summer cooling) standards, together with significantly lower annual delivered and prime energy consumption with lower maintenance requirements than even the best natural ventilation designs." [Braham 2000]

Thus, the future of both natural and mechanical ventilation now clearly lies in the emerging field of hybrid ventilation system design. However, this report is focused on natural ventilation as a stand-alone strategy. Future work will address hybrid approaches in more detail.

3. California Opportunities and Issues

This section discusses opportunities and issues in the application of natural ventilation systems to commercial buildings. These issues include climate suitability, ambient air quality, and codes and standards, and they are discussed in the context of application in the state of California.

3.1 Climate Suitability

One of the most important issues in determining the potential of natural ventilation systems is the suitability of the climate. A method to evaluate climate suitability based on a single-zone model of natural ventilation heat transfer in commercial buildings is presented in this section. This method is applied to specific climatic data to characterize:

- the statistical distribution of the natural direct ventilation rates needed to offset given internal heat gains rates (i.e., due to occupants, equipment and lighting) to achieve thermal comfort during overheated periods, and
- the potential internal heat gain that may be offset by night-time cooling for those days when direct ventilation is insufficient.

The theory and simplifying assumptions underlying this method will be discussed first followed by a presentation of the application of the method using TMY2 climatic data [Marion and Urban 1995] for ten California locations.

Theory

For preliminary climatic suitability analysis, a commercial building may be thermally idealized as a control volume with a uniform temperature distribution, i.e., the common single-zone representation of a building illustrated in Figure 6:

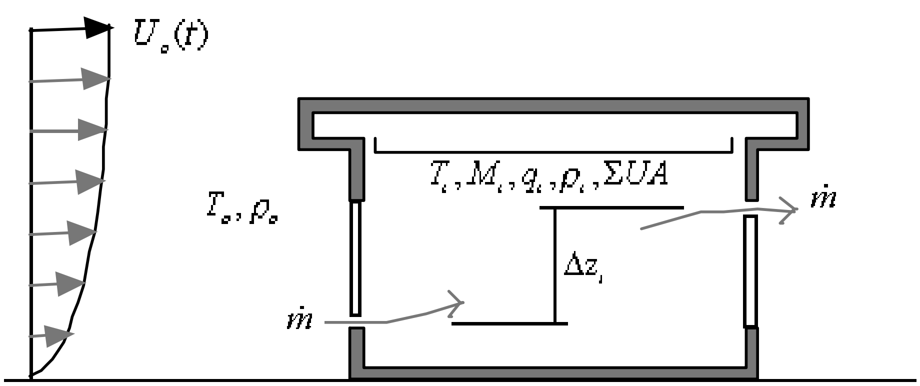

Figure 6 Single-zone model of a building

where:

$U_o(t)$ = the (outdoor) reference wind speed

$T_o(t)$ = the outdoor air temperature

$\rho_o(t)$ = the outdoor air density

$T_i(t)$ = the indoor air temperature

$\rho_i(t)$	=	the indoor air density
$q_i(t)$	=	indoor internal plus solar gains
M_i	=	indoor thermal mass
ΣUA	=	building envelope thermal conductance
$\dot{m}$	=	mass flow rate of ventilation air
Δz_i	=	inlet to outlet elevation change

With these model parameters and variables defined, the dynamic thermal behavior of this single-zone idealization may be defined by requiring the conservation of thermal energy:

$$\begin{pmatrix}\text{heat transfer}\\ \text{rate out}\end{pmatrix} + \begin{pmatrix}\text{thermal}\\ \text{energy accumulated}\end{pmatrix} = \begin{pmatrix}\text{heat transfer}\\ \text{rate in}\end{pmatrix} \tag{1}$$

or:

Dynamic Model

$$KT_i + M\frac{dT_i}{dt} = E \tag{2}$$

where:

$$K = \Sigma UA + \dot{m}c_P \tag{3}$$

$$E = KT_o + q_i \tag{4}$$

In this formulation, conductive heat transfer is arbitrarily separated into a rate of heat transfer out equal to the product of the envelope conductance and the indoor air temperature $(\Sigma UA)T_i$ and a rate of heat transfer in $(\Sigma UA)T_o$. Thus, the net conductive heat transfer rate is the more familiar product of the envelope conductance and the outside-to-inside temperature difference $(\Sigma UA)(T_o - T_i)$. Similarly and more intuitively direct, the ventilative heat transfer rate is separated into a rate out $\dot{m}c_pT_i$ – where c_p is the specific heat capacity of air (1.006 kJ/kg·°K or 0.24 kcal/kg·°K for dry air) – and a rate in $\dot{m}c_pT_o$. Together, the combined conductive and ventilative heat transfer rate out of the control volume is, thus, KT_i where K is the combined conductive and ventilative transfer coefficient defined by Equation (3). This formulation stresses the fact that the response of the thermal system is excited by the sum of conductive, ventilative, and internal gains $KT_o + q_i$ that are defined by Equation (4) to be the system *excitation E.*

If either the thermal mass M_i of the building system is negligibly small or the indoor air temperature T_i is regulated to be relatively constant, then the accumulation term of the governing energy balance of the system, Equation (2), may become insignificantly small. Under these conditions the thermal response of the building system will be governed by the steady-state limiting case of Equation (2) or:

Steady State Model

$$KT_i = E \tag{5}$$

This steady-state approximation is the essential basis of the heating and cooling degree day methods used for preliminary determination of annual heating or cooling energy needs and as metrics of a given climate's heating and cooling season. It will also provide an approximate means to characterize the ventilative cooling potential of a given climate.

The so-called *heating balance point temperature* T_{o-hbp} establishes the outdoor air temperature below which heating must be provided to maintain indoor air temperatures at a desired internal heating set point temperature T_{i-hsp} . Hence, when outdoor temperatures exceed the balance point temperature direct ventilative cooling can usefully offset internal heat gains to maintain thermal comfort. At or below the balance point temperature, ventilative cooling is no longer useful although ventilation should still be maintained at the minimum level required based on air quality considerations.

At the heating balance point the combined conductive and ventilative heat loss from the building just offsets internal gains or, using the steady state approximation:

$$\textit{Heating Balance Point}\text{:}\ K\left(T_{i-hsp} - T_{o-hbp}\right) = q_i \qquad (6)$$

Solving this equation for the balance point temperature and expanding we obtain:

$$T_{o-hbp} = T_{i-hsp} - \frac{q_i}{\dot{m}_{\min} c_p + \Sigma UA} \qquad (7)$$

where the ventilation flow rate has been set to the minimum ventilation rate required for air quality control $\dot{m}_{\min}$.

The heating balance point temperature, based on a prescribed heating set point temperature equal to the lowest indoor air temperature that is acceptable for thermal comfort, establishes a lower bound of acceptable outdoor temperatures for ventilative cooling. The outdoor air temperatures equal to the highest acceptable temperature for thermal comfort establishes an upper bound above which ventilative cooling will not be useful. Here, this limiting temperature will be assumed to be equal the indoor cooling set point temperature T_{i-csp} above which mechanical cooling would normally be activated to maintain thermal comfort. In addition, indoor air humidity must be limited to achieve comfortable conditions and to avoid moisture-related problems.

Distinct thermal comfort limits or *comfort zones* may be identified for summer conditions, when occupants tend to wear lighter clothing, and winter conditions, when occupants tend to wear heavier clothing. However, due to internal gains, natural ventilation may be expected to be useful to limit overheating in commercial buildings during both summer and cooler periods of the year. Consequently, for ventilative cooling of commercial buildings it is useful to use a combined comfort zone that covers all seasons of the year.

A reasonable comfort zone for ventilative cooling, based on combining ASHRAE's winter and summer comfort zones [ASHRAE, 1997], would be delimited by lower and upper dry bulb temperatures of 20 °C (68 °F) and 26 °C (79 °F) and a dew point temperature of 17 °C (63 °F) as illustrated in figure 7. Thus for all subsequent considerations:

- the indoor heating set point temperature will be assumed to be $T_{i-hsp} = 20\,°\text{C}$ (68 °F),
- the indoor cooling set point temperature will be assumed to be $T_{i-csp} = 26\,°\text{C}$ (79 °F), and
- indoor air humidity will be limited to a dew point temperature of $T_{i-dp} = 17\,°\text{C}$ (63 °F).

Recent surveys of comfort in naturally ventilated office buildings in the U.K. indicate occupants tolerate a larger range of temperatures than in air-conditioned buildings. This is thought to be due to occupant *adaptive* behavior that is fostered by these buildings [Olesen 2000, Oseland 1998]. When occupant adaptive behavior is considered, the upper limit of the comfort zone may, arguably, be increased by approximately 2 °C (4 °F) in still air conditions and even more when occupants can control local air speeds. Furthermore, slightly higher relative humidities may be tolerated when local air speeds of around 1.5 m/s (27 ft/min) are available [Martinez 2000]. Thus, the comfort zone used here may be considered somewhat conservative if adaptive behavior is considered and the ventilation system is designed to provide relatively high local air speeds.

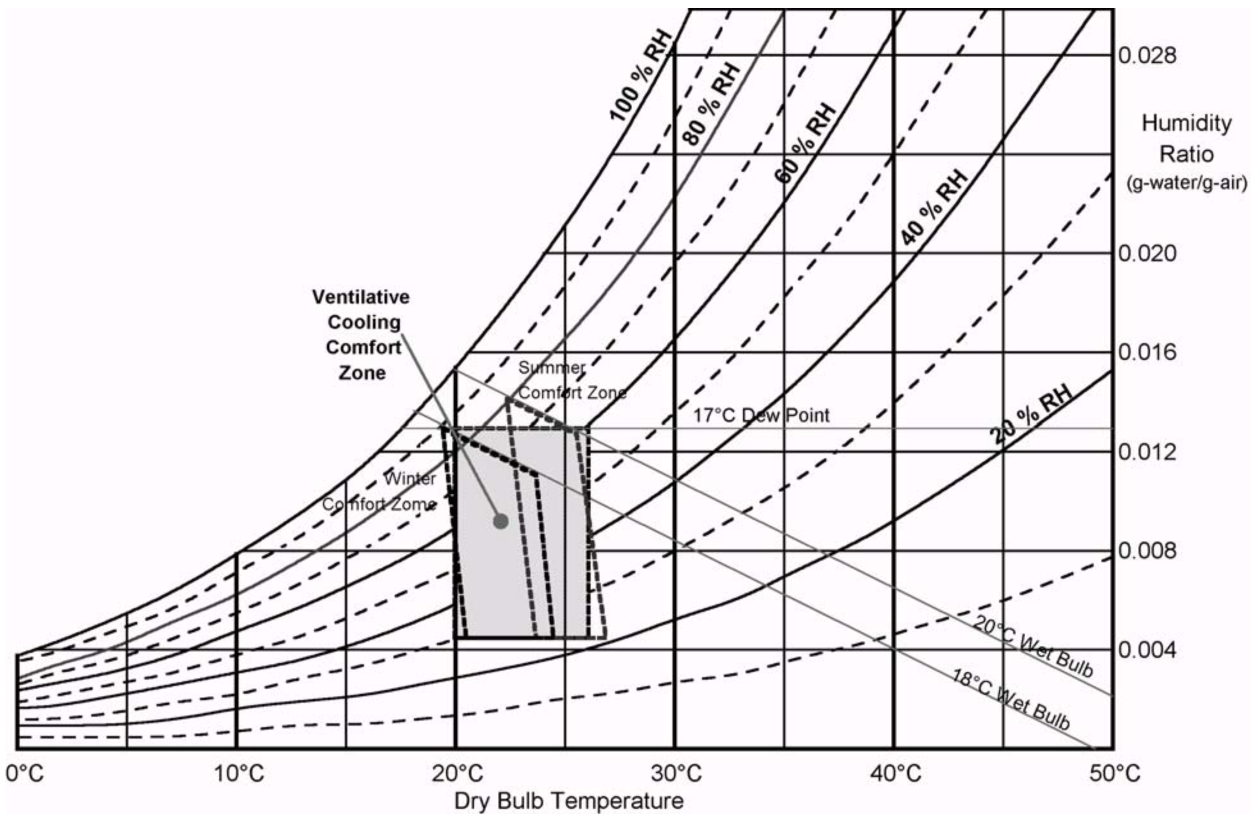

Figure 7 Comparison of the ventilative cooling comfort zone used in the present study with ASHRAE summer and winter comfort zones [ASHRAE 1997].

Thus, direct ventilative cooling will be considered to be useful (although perhaps not sufficient) when outdoor conditions fall below both the cooling set point and the dew point limit yet above the outdoor heating balance point temperature determined based on the indoor heating set point temperature limit above. Formally, these conditions may be defined as:

Direct Ventilative Cooling Criteria:

$$T_{o-hbp}(q_i, T_{i-hsp} = 20\,°\text{C}) \le T_o \le T_{i-csp} = 26\,°\text{C} \quad \text{and} \quad T_{o-dp} \le 17\,°\text{C} \tag{8}$$

For night ventilative cooling, no lower limit need be placed on outdoor air temperatures and while the air humidity limit is not likely to be immediately important for thermal comfort reasons, it will be maintained to avoid moisture-related problems in building materials and furnishings:

Night Ventilative Cooling Criteria:

$$T_o \le T_{i-csp} = 26\,°\text{C} \quad \text{and} \quad T_{o-dp} \le 17\,°\text{C} \tag{9}$$

Method

With the theory and comfort criteria established above, a method to evaluate the suitability of a given climate for ventilative cooling may be formulated. This method involves a procedure for estimating the ventilation rate needed to offset internal gains when direct ventilation can be effective and a second procedure for estimating the internal gains that may be offset by nighttime ventilation when direct ventilation is not useful.

DIRECT VENTILATION

Relative to their enclosed volume, commercial buildings typically have relatively small envelope surface areas yet require relatively large minimum ventilation rates for air quality control. Consequently, the conductive conductance of commercial buildings ΣUA may be expected to be small relative to the minimum ventilative conductance $\dot{m}_{\min} c_p$:

$$\dot{m}_{\min} c_p >> \Sigma UA \tag{10}$$

Thus, the heating balance point temperature of commercial buildings – which is approached from above as ventilation is reduced to the minimum value needed for air quality control – may be estimated by introducing the condition of Equation (10) into Equation (7) to obtain:

$$T_{o-hbp} = T_{i-hsp} - \frac{q_i}{\dot{m}_{\min} c_p + \Sigma UA} \approx T_{i-hsp} - \frac{q_i}{\dot{m}_{\min} c_p} \tag{11}$$

or, in terms of rates per unit floor area of building:

$$T_{o-hbp} \approx T_{i-hsp} - \frac{q_i / A}{\left(\dot{m}_{\min} / A\right) c_p} \tag{12}$$

When outdoor air temperatures exceed this balance point temperature, yet fall below the upper limit of the comfort zone – here, taken as the indoor cooling set point temperature T_{i-csp} – ventilation can offset a given internal gain. Again, assuming ventilative conductance dominates heat transfer (i.e., $\dot{m} c_p >> \Sigma UA$), the ventilation rate required to offset internal gains while maintaining indoor air temperatures within the comfort zone, $\dot{m}_{cool}$, may be estimated using the steady state model, Equation (5). Given the width of the comfort zone $(T_{i-csp} - T_{i-hsp})$, however, two possibilities must be considered. When outdoor air temperatures fall within an increment of $(T_{i-csp} - T_{i-hsp})$ above the balance point temperature, the minimum ventilation rate will suffice:

$$\dot{m}_{cool} = \dot{m}_{\min} \quad when \quad T_{o-hbp} \le T_o \le T_{o-hbp} + (T_{i-csp} - T_{i-hsp}) \tag{13}$$

Above this range, the ventilation rate will have to increase as outdoor air temperatures increase:

$$\dot{m}_{cool} = \frac{q_i}{c_p (T_{i-csp} - T_o)} \quad when \quad T_{o-hbp} + (T_{i-csp} - T_{i-hsp}) < T_o \le T_{i-csp} \tag{14}$$

or, in terms of rates per unit floor area of building:

$$\dot{m}_{cool} / A = \frac{q_i / A}{c_p (T_{i-csp} - T_o)} \quad when \quad T_{o-hbp} + (T_{i-csp} - T_{i-hsp}) < T_o \le T_{i-csp} \tag{15}$$

Equations (12), (13), and (15) may be used to determine periods when direct ventilative cooling may be applied and to estimate the ventilation rates needed to maintain thermal comfort during these periods. For comparative purposes, it will be useful to further express the ventilation rates in terms of an equivalent air change rate ACH in air changes per hour (h^{-1}) by assuming an average story height of the building, H, as:

$$ACH \approx \frac{\dot{m}_{cool}}{A\,H} \tag{16}$$

NIGHTTIME COOLING

To account for night cooling an alternative strategy must be employed. When daytime outdoor temperatures exceed the upper comfort limit – here, taken as the cooling set point temperature T_{i-csp} – direct ventilation is no longer useful. One may be able to offset daytime internal gains, however, by cooling the building's thermal mass with outdoor air during the previous night if, of course, the outdoor air temperature drops below the cooling set point temperature during the night. When this is possible, the heat transfer rate at which energy may be removed from the buildings thermal mass q_{night} approaches, in the limit for a very massive building:

$$q_{night} \approx \dot{m}c_p\left(T_{i-csp} - T_o\right) \;\; when \;\; T_o < T_{i-csp} \tag{17}$$

The total energy removed from the building's thermal mass during the evening may then be used to offset internal gains on the subsequent workday. On average, the internal gain that may be offset $\overline{q}_{cool}$ is thus simply equal to the integral of the night removal rate divided by the workday time period Δt:

$$\overline{q}_{cool} = \int_{nighttime} q_{night} \Big/ \Delta t \tag{18}$$

Here, it is useful to rewrite this relation in terms of average cooling rate per unit floor area per air change rate by algebraic manipulation:

$$\frac{\overline{q}_{cool}/A}{\dot{m}/A\,H} = \frac{\int_{nighttime} c_p\left(T_{i-csp} - T_o\right)dt}{H\,\Delta t} \;\; when \;\; T_o < T_{i-csp} \tag{19}$$

Equation (19) will be used to estimate the internal gain that may be offset (i.e., for very massive construction) for a nominal unit nightime air change rate to maintain thermal comfort.

<u>Climate Suitability Evaluation Algorithm</u>

The relations and criteria established above were used to develop a multi-step algorithm to evaluate the suitability of a given climate for ventilative cooling. Given detailed records of outdoor dry bulb and dew point temperatures the algorithm involves the following steps:

A. Problem Specification: The cooling and heating set point temperatures, limit on dew point temperatures, specific internal gains, and minimum specific ventilation rate, or the equivalent air change rate are specified. Specifically, in this analysis:

- The cooling set point temperature was set equal to the upper limit of the ventilative cooling comfort zone, $T_{i-csp} = 26\,°C$ (79 °F)
- The heating set point temperature was set equal to the lower limit of the ventilative cooling comfort zone, $T_{i-hsp} = 20\,°C$ (68 °F)

- The limiting outdoor dew point temperature was set equal to the upper limit of the ventilative cooling comfort zone, $T_{o-dp} = 17\,°\mathrm{C}$ (63 °F)
- Specific internal gains of 10 W/m^2 (3.2 Btu/ft^{2}h), 20 W/m^2 (6.3 Btu/ft^{2}h), 40 W/m^2 (12.6 Btu/ft^{2}h), and 80 W/m^2 (25.2 Btu/ft^{2}h) were considered. The low end of this range corresponds to the combination of state-of-the-art low-energy lighting systems combined with minimal plug-loads in addition to relative low occupant densities. The upper end corresponds to very intensive lighting, plug loads, and occupancy levels that might be associated with, for example, commodities trading floors. While this range is commonly considered for commercial building design purposes, recent research indicates the upper levels of this range may no longer be realistic [Komor 1997, Wilkins and Hosni 2000].
- ASHRAE Standard 62 [ASHRAE 1999] prescribes minimum ventilation rates for commercial buildings. Here, the rates specified for offices will be used to establish a typical minimum specific ventilation rate. Due to relatively low occupancy levels (e.g., 7 persons per 100 square meters (7 persons per 1100 square feet)) and moderate rate requirements (i.e., 10 Liters per second per person (21 cubic feet per minute per person)) for offices, the specific ventilation rate required for offices is 0.7 L/s•m^2 (0.14 ft^3/min•ft^2) ($\dot{m}_{\min}$ / A ≈ 0.0084 kg/s•m^2 (0.0017 lb/s•ft^2) for air at standard conditions). For an assumed story height of H = 2.5 m (8.2 ft), this minimum specific ventilation rate corresponds to an air change rate of about 1.0 h^{-1}.

B. Balance Point Temperature Computation: Compute the outdoor heating balance point temperature for each specific internal gain considered as follows:

$$T_{o-hbp} \approx T_{i-hsp} - \frac{q_i / A}{c_p \dot{m}_{\min} / A}$$

For the conditions specified above in Step 1, we obtain the following results in Table 1.

Table 1 Heating balance point temperatures for a range of specific internal gains.

	Specific Internal Gains (q_i / A)			
	10 W/m^2	20 W/m^2	40 W/m^2	80 W/m^2
T_{o-hbp}	8.1 °C	– 3.8 °C	– 27.6 °C	– 75.2 °C

It is evident from these numbers that internal gains expected in commercial buildings can quite easily extend the ventilative cooling season well into winter months.

C. Direct Ventilative Cooling Evaluation: For each hour of an annual climatic record for a given location proceed through the following steps:

C.1. If $T_o < T_{o-hbp}$ no ventilative cooling will be required.

C.2. If $T_{o-hbp} \leq T_o \leq T_{o-hbp} + \left(T_{i-csp} - T_{i-hsp}\right)$ and $T_{o-dp} \leq 17\,°\mathrm{C}$ (63 °F) the cooling ventilation rate may be maintained at the minimum ventilation rate, $\dot{m}_{cool} = \dot{m}_{\min}$ while the indoor air temperature T_i floats between the balance point temperatures. Record the corresponding air change rate $ACH \approx \dot{m}_{cool} / (A\,H)$.

C.3. If $T_{o-hbp} + \left(T_{i-csp} - T_{i-hsp}\right) \leq T_o < T_{i-csp}$ and $T_{o-dp} \leq 17\,°\text{C}$ (63 °F) the minimum cooling ventilation rate needed to maintain indoor air conditions within the comfort zone (i.e., at the cooling set point temperature) may be computed as:

$$\frac{\dot{m}_{cool}}{A} = \frac{q_i / A}{c_p (T_{i-csp} - T_o)}$$

Record the corresponding air change rate $ACH \approx \dot{m}_{cool} / (A\,H)$.

C.4. Else if $T_o > T_{i-csp}$ or $T_{o-dp} > 17\,°\text{C}$ (63 °F) then ventilative cooling is not useful. Record this condition for subsequent evaluation of cooling using nighttime ventilation.

D. Nighttime Ventilative Cooling Evaluation:

D.1. Scan the results of step C to identify days for which direct ventilative cooling was not useful for at least one daytime hour.

D.2. For each day identified in D.1, compute the (limiting) rate at which thermal energy can be removed from the building's thermal mass for each hour of the proceeding night (i.e., from 6 p.m. to 6 a.m.) as:

$$q_{night} \approx \dot{m} c_p \left(T_{i-csp} - T_o\right) \text{ when } T_o < T_{i-csp} \text{ and } T_{o-dp} \leq 17\,°\text{C (63 °F)}$$

D.3. Using the results from 4.2 compute the average internal gain that may be offset $\overline{q}_{cool}$ the next day:

$$\frac{\overline{q}_{cool} / A}{\dot{m} / A\,H} = \frac{\int_{nighttime} q_{night}\, dt}{H\, \Delta t}$$

<u>Climatic Data</u>

In the application of this method that follows, TMY2 (Typical Meteorological Years) data were used [Marion and Urban 1995]. The TMY2 data sets were devised to be “typical year” data sets intended to be used to evaluate typical year meteorological conditions. Thus, the TMY2 data should be useful for evaluating the climatic suitability (potential) of a given site for natural ventilation applications in buildings for typical year conditions. Another option when evaluating the performance of a specific (proposed) natural ventilation system would be to consider extreme year rather than typical year conditions. Levermore and his colleagues have taken this position, defining an extreme year as the mid-year of the upper quartile of 20 years’ climatic data ordered by the average daily mean temperatures for July, August, and September [Levermore et al. 2000].

<u>Discussion of Method</u>

A method to evaluate the climate suitability of a given location for direct ventilative cooling and complimentary nighttime ventilative cooling of a building's thermal mass has been presented. Importantly, the method may be applied, in principle, to ventilative cooling achieved by natural, mechanical, or mechanically assisted natural means. This method allows the building designer to quickly evaluate the feasibility and potential effectiveness of ventilative cooling strategies, given knowledge of the likely internal gains in the building, and make first estimates of the ventilation rates required to effect these strategies.

The proposed method has a rational physical basis and therefore should be considered relatively general. Furthermore, the method has been devised to provide building designers with useful preliminary design guidance relating to the levels of ventilation required to implement the direct and nighttime cooling strategies.

The method is not without its faults, however. First, estimates of the internal gains that may be offset by nighttime cooling are based on the assumption that the building has, essentially, infinite thermal mass. Thus, these results may significantly overestimate the benefit of nighttime cooling. This fault could be corrected with a measure of heat transfer efficiency that reflects the anticipated level of thermal mass available in the building, but this correction would require additional research using a dynamic formulation of the building heat transfer.

As presented, the climate suitability analysis tacitly assumed the temperature of the ventilation exhaust was equal to the indoor occupied zone temperature – a condition that would be met if the building zone was well-mixed. The analysis, being based on a control volume approach, need not be limited to a well-mixed zone assumption – the exhaust air temperature should simply reflect the intended operation of the ventilation system being used. If, for example, one seeks to drive ventilation airflows primarily by buoyancy forces then allowing temperature stratification within the building offers some advantages [Linden 1999, Hunt et al. 2000, Hunt et al. 2001]. In such a case, exhaust air temperatures could exceed comfort limits (e.g., the indoor cooling set point) by an increment corresponding to that resulting from acceptable or likely stratification, say, $\Delta T_{strat} = T_{i-strat} - T_{i-csp}$. For direct ventilative cooling, then, the ventilation rate per unit floor area needed to offset a given internal gain (i.e., Equation 1.15) would be modified as:

$$\dot{m}_{cool}/A = \frac{q_i/A}{c_p(\Delta T_{strat} + T_{i-csp} - T_o)} \quad when \quad T_{o-hbp} + (T_{i-csp} - T_{i-hsp}) < T_o \leq T_{i-csp}$$

and analysis would proceed as before. Thus, for example, if a designer feels a 4 ºC stratification increment is acceptable (i.e., if exhaust temperatures can exceed the upper comfort limit by 4 ºC) then the analysis would proceed with the temperature term of the denominator above increased by 4 ºC thus reducing the ventilation rate needed at any time step during the analysis.

In this way, the reduced ventilation rate benefit of utilizing thermal stratification – in combination with displacement ventilation – may be accounted for. The risk of compromising thermal comfort by radiant exchange from warm ceilings should, however, be considered. For all but the tallest commercial buildings, however, wind forces are likely to play a more important role in natural and hybrid ventilation systems than buoyancy forces as will be discussed in the next chapter – thus consideration of thermal stratification may not be necessary.

Also, the method presumes direct ventilative cooling should be the strategy of first resort and nighttime ventilative cooling should only be considered as a complement to direct cooling. As such, this method does not evaluate the potential of nighttime ventilative cooling as a primary strategy. Conceivably, in some climates or for certain applications nighttime cooling may be more appropriate as the primary strategy. This situation should be investigated in the future.

Application to California climates

This method was applied to the ten California locations with TMY2 hourly annual climatic data available. While the ten locations, listed in Table 2 below, do not statistically represent the state in terms of population or climate, they do include both coastal and inland climates that cover much of the latitudinal range of the state.

Table 2 California locations used for initial climate suitability evaluation.

Coastal	Inland
San Diego	*Daggett*
Long Beach	*Bakersfield*
Los Angeles	*Fresno*
Santa Maria	*Sacramento*
San Francisco	
Arcata	

Computed results follow in Table 3. Data in this table is organized in two sets – a set of four columns that report the direct ventilative cooling results:

- the average air change rate required to effect direct ventilative cooling for each of four specific internal gain rates for each of the ten California locations – *when direct cooling is effective*,
- the variation of the air change rate about the average value to be expected for each case – evaluated by computing the standard deviation of the ventilation rates computed to achieve thermal comfort, and
- the fraction of the year direct cooling is effective for each case – i.e., the number of hours direct ventilation is effective out of the total number of hours in a year's record.

A final column reports the results for complimentary night cooling:

- the average specific internal gain that can be offset by a nominal unit air change rate of (previous) nighttime cooling for overheated days (i.e., those days when direct ventilative cooling is not effective for all hours from 6 a.m. to 6 p.m.),
- the fraction of overheated days that may, potentially, be cooled using nighttime ventilation,
- and the total number of days during the year that nighttime cooling may, potentially, be effective.

These statistics have been devised to provide design guidance for preliminary considerations. To facilitate preliminary design considerations, the direct ventilative cooling results are shaded to distinguish the ranges of ventilation required. Results in white or light gray boxes will require, on average, ventilation rates in the 0 h^{-1} to 5 h^{-1} and 5 h^{-1} to 10 h^{-1} ranges respectively – both quite possible using commonly available natural ventilation strategies. Results in medium and darker gray (10 h^{-1} to 15 h^{-1} and above 15 h^{-1}) may be difficult to achieve using available natural ventilation strategies.

For example, the results for Bakersfield show that an average ventilation rate of 3.4 h^{-1} ± 8.7 h^{-1} may be expected to provide direct ventilative cooling when the specific internal gain is 10 W/m^2 (3.2 Btu/ft^2h). Furthermore, for this location, direct ventilative cooling may be expected to be useful 64 % of the hours of the year for this same specific internal gain. Nighttime cooling can be used in this climate to compliment direct cooling for 93 days of the year that accounts for 94 % of the expected overheated days. Thus 6 % of these overheated days (approximately 11 days) would require mechanical air conditioning to achieve thermal comfort. During the 159 days with possible nighttime ventilative cooling, internal gains can be offset at the rate of 3.2 W/m^2-h^{-1} ± 2.6 W/m^2-h^{-1} (1.0 Btu/ft^2h-h^{-1} ± 0.81 Btu/ft^2h-h^{-1}). Thus to offset a specific internal gain of 10 W/m^2 (3.2 Btu/ft^2h), the nighttime ventilation rate would have to be $10 \div 3.2 \geq 3.1\ h^{-1}$ on average. (Here, the ≥ sign is used as the $\overline{q}_{cool}$ computation is based on the assumption that the building is thermally massive.)

Table 3 Climate suitability statistics for ten California locations

	Direct Cooling				
	10 W/m^2	20 W/m^2	40 W/m^2	80 W/m^2	Night Cooling[1]
Arcata					
Vent. Rate or Cooling Potential	**(1.1 ±0.4) h^{-1}**	**(1.7 ±0.8) h^{-1}**	**(3.3 ±1.7) h^{-1}**	**(6.7 ±3.4) h^{-1}**	**10.5 ±1.5 W/m^2•h^{-1}**
% Effective[2]	**74 %**	**100 %**	**100 %**	**100 %**	**100 % (2 days)**
% Heating	**26 %**	**0 %**	**0 %**	**0 %**	
Bakersfield					
Vent. Rate or Cooling Potential	**(3.4 ±8.7) h^{-1}**	**(5.7 ±16.1) h^{-1}**	**(11.5 ±32.2) h^{-1}**	**(22.9 ±64.3) h^{-1}**	**(3.2 ±2.6) W/m^2•h^{-1}**
% Effective[2]	**64 %**	**77 %**	**77 %**	**77 %**	**94 % (159 days)**
% Heating	**12 %**	**0 %**	**0 %**	**0 %**	
Daggett					
Vent. Rate or Cooling Potential	**(3.4 ±8.9) h^{-1}**	**(5.8 ±16.5) h^{-1}**	**(11.6 ±32.9) h^{-1}**	**(23.2 ±65.8) h^{-1}**	**(3.7 ±2.9) W/m^2•h^{-1}**
% Effective[2]	**60 %**	**71 %**	**71 %**	**71 %**	**86 % (169 days)**
% Heating	**11 %**	**0 %**	**0 %**	**0 %**	
Fresno					
Vent. Rate or Cooling Potential	**(2.9 ±7.2) h^{-1}**	**(4.6 ±12.8) h^{-1}**	**(9.2 ±25.6) h^{-1}**	**(18.3 ±51.1) h^{-1}**	**(4.3 ±2.8) W/m^2•h^{-1}**
% Effective[2]	**63 %**	**81 %**	**81 %**	**81 %**	**100 % (161 days)**
% Heating	**18 %**	**0 %**	**0 %**	**0 %**	
Long Beach					
Vent. Rate or Cooling Potential	**(2.3 ±5.6) h^{-1}**	**(4.4 ±11.1) h^{-1}**	**(8.7 ±22.1) h^{-1}**	**(17.4 ±44.3) h^{-1}**	**(6.2 ±2.7) W/m^2•h^{-1}**
% Effective[2]	**88 %**	**91 %**	**91 %**	**91 %**	**92 % (95 days)**
% Heating	**3 %**	**0 %**	**0 %**	**0 %**	
Los Angeles					
Vent. Rate or Cooling Potential	**(1.7 ±1.9) h^{-1}**	**(3.3 ±3.8) h^{-1}**	**(6.6 ±7.7) h^{-1}**	**(13.2 ±15.4) h^{-1}**	**(6.6 ±2.2) W/m^2•h^{-1}**
% Effective[2]	**96 %**	**97 %**	**97 %**	**97 %**	**100 % (55 days)**
% Heating	**1 %**	**0 %**	**0 %**	**0 %**	
Sacramento					
Vent. Rate or Cooling Potential	**(2.3 ±6.5) h^{-1}**	**(3.8 ±11.6) h^{-1}**	**(7.6 ±23.2) h^{-1}**	**(15.1 ±46.4) h^{-1}**	**(7.0 ±2.2) W/m^2•h^{-1}**

% Effective[2]	**69 %**	**88 %**	**88 %**	**88 %**	**100 % (142 days)**
% Heating	**19 %**	**0 %**	**0 %**	**0 %**	
San Diego					
Vent. Rate or Cooling Potential	**(1.8 ±3.3) h^{-1}**	**3.6 ±6.5 h^{-1}**	**(7.2 ±13.0) h^{-1}**	**(14.5 ±26.1) h^{-1}**	**(3.6 ±2.3) $W/m^2 \bullet h^{-1}$**
% Effective[2]	**91 %**	**92 %**	**92 %**	**92 %**	**90 % (52 days)**
% Heating	**1 %**	**0 %**	**0 %**	**0 %**	
San Francisco					
Vent. Rate or Cooling Potential	**(1.3 ±1.3) h^{-1}**	**(2.2 ±2.6) h^{-1}**	**(4.5 ±5.1) h^{-1}**	**(8.9 ±10.3) h^{-1}**	**(8.6 ±2.6) $W/m^2 \bullet h^{-1}$**
% Effective[2]	**90 %**	**99 %**	**99 %**	**99 %**	**100 % (12 days)**
% Heating	**10 %**	**0 %**	**0 %**	**0 %**	
Santa Maria					
Vent. Rate or Cooling Potential	**(1.4 ±1.8) h^{-1}**	**(2.4 ±3.4) h^{-1}**	**(4.9 ±6.9) h^{-1}**	**(9.7 ±13.8) h^{-1}**	**(11.2 ±2.8) $W/m^2 \bullet h^{-1}$**
% Effective[2]	**82 %**	**99 %**	**99 %**	**99 %**	**100 % (17 days)**
% Heating	**17 %**	**0 %**	**0 %**	**0 %**	

[1] Night cooling for subsequent days when direct cooling is not effective.

[2] For direct cooling % = hours effective ÷ 8760 h; for night cooling % = days effective ÷ days needed.

white = 0 h^{-1} to 5 h^{-1}

light gray = 5 h^{-1} to 10 h^{-1}

medium gray = 10 h^{-1} to 15 h^{-1}

dark gray > 15 h^{-1}

The data presented in Table 3 has been plotted in the form of *bubble* plots for the six coastal locations and the four inland locations – Figure 8 and Figure 9. In these plots the center of each bubble locates the average ventilation rate required for each of the four specific internal gain rates considered and the size of the bubble indicates the relative efficacy of direct ventilative cooling. Thus larger bubbles located lower in the plot indicate direct ventilative cooling is not only feasible (vis a vis ventilation rate required) but effective.

As might be expected, Table 3 and Figure 8 show that the coastal climates of California are potentially well suited to natural ventilation with respect to climatic considerations. For most of these locations, the direct ventilative cooling approaches 90 % to 100 % effectiveness with most of the ineffective hours representing either times when heating is required or times that could be cooled through night ventilative cooling. Equally significant is the fact that, for buildings with moderate internal gains in most of these locations, the required cooling can be achieved with very achievable average air change rates of about 5 h^{-1} or less. Additionally, with the exception of Long Beach, the required air change rates have reasonable standard deviations less than or about equal to the averages. The required air change rates for the buildings with higher internal loads may be achievable with new and developing natural ventilation technology.

On the other hand, natural ventilation appears to be less promising for the hotter, more humid climates of inland California. As shown in Table 3 and Figure 9 for the four inland locations, both direct and night ventilative cooling have a lower percentage effectiveness and require larger air change rates (with much larger standard deviations) then for the coastal locations. Despite that, a significant ventilative cooling potential exists for these locations. However, some type of hybrid system with mechanical cooling may be more successful in these situations.

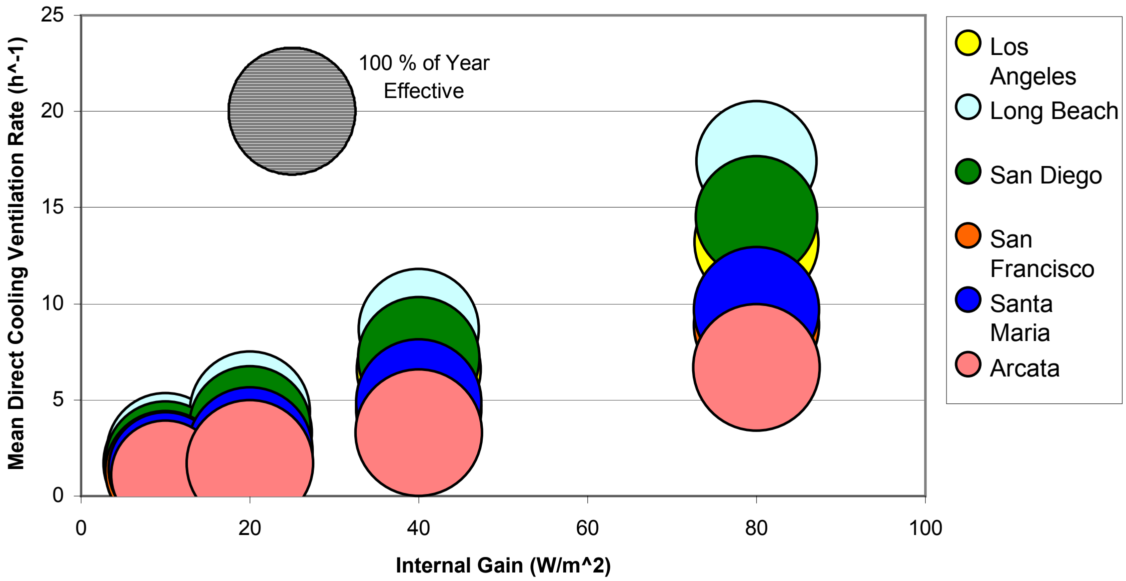

Figure 8 Direct ventilative cooling results for the coastal locations.

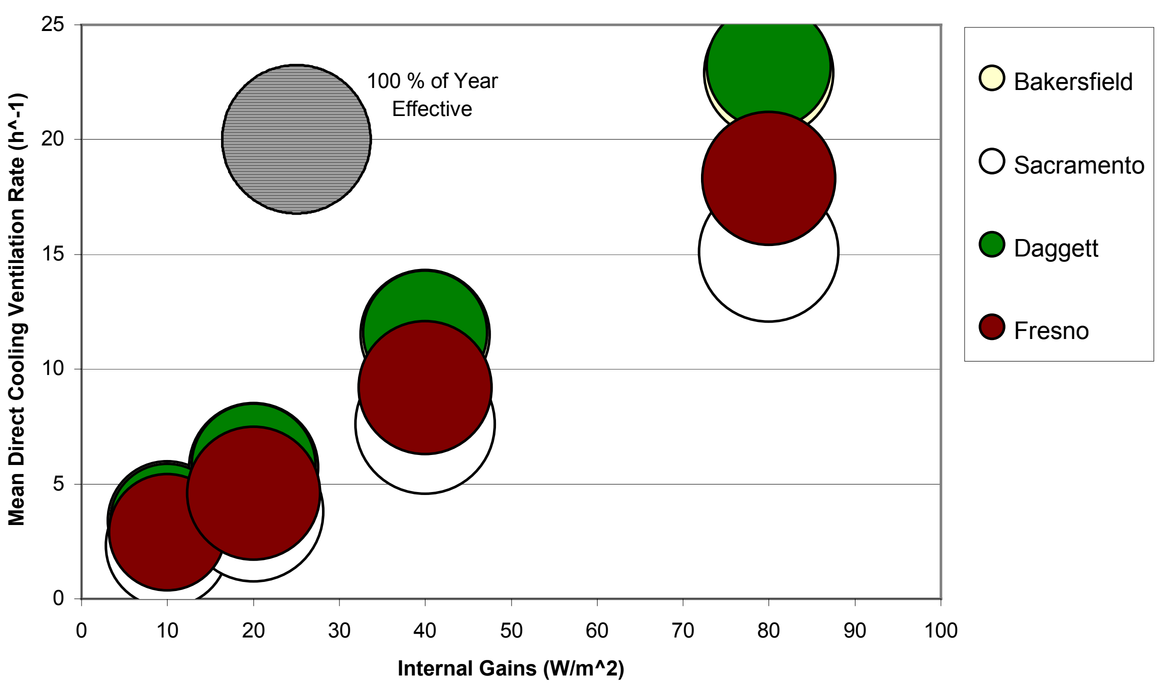

Figure 9 Direct ventilative cooling results for the inland locations

3.2 Ambient Air Quality

A second important issue in determining the potential for natural ventilation systems in California and elsewhere is the impact of ambient air quality. While poor ambient air quality affects both mechanical and natural ventilated buildings, there are two reasons for greater concern with natural ventilation. First, as discussed in the review section, typical natural ventilation systems do not incorporate filtration. Although the filtration in mechanical ventilation systems does not remove all contaminants from the outdoor air, it generally includes some form of particle filtration. Second, in order to perform ventilative cooling, natural ventilation systems may introduce far greater quantities of outdoor air into the building.

Ideally, one would develop a metric to express the suitability of the outdoor air quality in a given location as has been presented above for climate suitability. Unfortunately, the issue is not nearly so straightforward due to knowledge gaps such as the lack of specific health-based, contaminant concentration limits for indoor air and less standardized ambient air quality data compared with weather data. However, ASHRAE Standard 62-1999 [ASHRAE 1999] requires that the outdoor air used for ventilation in buildings meet the National Primary Ambient-Air Quality Standards set by the U.S. EPA [EPA 1987] which sets concentration limits for sulfur dioxide, particles (as PM10), carbon monoxide, ozone, nitrogen dioxide, and lead. Additionally, California has established somewhat more restrictive ambient air quality limits than the national standards for some of these contaminants [CARB 2001].

Standard 62 allows several alternatives for determining whether the local ambient air quality meets the prescribed limits including monitoring data of the U.S. EPA or appropriate state or local environmental protection authorities. If outdoor air contaminant levels exceed the limits, Standard 62 recommends that the outdoor air be treated to control the offending contaminants. As discussed earlier, natural ventilation systems typically do not include air filtration, however, the air cleaning equipment typically included in mechanical ventilation systems is unlikely to significantly impact the concentrations of ambient air pollutants other than coarse particles (i.e., larger than about 3 μm).

Although the acceptability of ambient air for ventilation purposes must be evaluated locally, available ambient air quality data for California [CARB 2001] were reviewed to gain some insight to the issue on a regional level. For the purpose of ambient-air quality evaluations, California is divided into 15 regions called air basins (Figure 10). If the air quality in an area violates an ambient air quality standard that region is designated with the status of nonattainment. This summary addresses nonattainment status based on the national standards. A nonattainment status alone, however, does not tell the complete story of the severity of an ambient air quality problem because it does not address the magnitude, frequency, or localization of the air quality violation.

California has undertaken many emission control measures for the last three decades and, as a result, significant improvements have been made in ambient air quality. However, three of the criteria contaminants still pose a problem for portions of the state as indicated by nonattainment. Most of the major, urban areas of California are nonattainment for the national 1-hour standard for ozone (see Figure 10). Some additional areas (Shasta, Tehama, Western Nevada, Amador, Calaveras, Tuolumne, and Mariposa counties) are nonattainment for the new, proposed 8-hour standard for ozone. Statewide attainment status for ozone is not expected in the near future. A significant portion of the state is also nonattainment for PM10 (see Figure 10). Four areas (the Coachella Valley, the Owens Valley, the San Joaquin Valley, and the South Coast Air Basin) are classified as serious PM10 nonattainment areas and are not expected to meet standards for many years. The South Coast Air Basin is designated nonattainment for national CO standards (see

Figure 10). However, this problem is specifically limited to a portion of Los Angeles County and is expected to be mitigated in the coming years. The city of Calexico also has carbon monoxide concentrations that violate the national standards but has not been designated nonattainment.

Although the nonattainment issues discussed above seem to discourage the application of natural ventilation systems in much of California, opportunity still lies in the fact that pollutant concentrations that violate the air quality standards may be local and/or seasonal phenomena even within nonattainment regions. Obviously, the local variation indicates that natural ventilation may still be a viable option for some buildings within these nonattainment areas. Also, as seen in Figure 10, the areas with better ambient air quality include much of the coastal area which was shown to have high climate suitability for natural ventilation as discussed in Section 3.1. Perhaps less obvious is the possibility that an area with a seasonal ambient air quality problem may be able to take advantage of some type of hybrid HVAC system that reduces outdoor air intake and/or treats outdoor air during the problem seasons. Even if ambient concentrations of some pollutants exceed recommended limits, the indoor levels may be acceptable due to deposition or other removal mechanisms. A multizone IAQ model such as CONTAM could be used to predict indoor pollutant concentrations resulting from various scenarios of different ventilation rates, ambient concentrations, and indoor generation or removal processes.

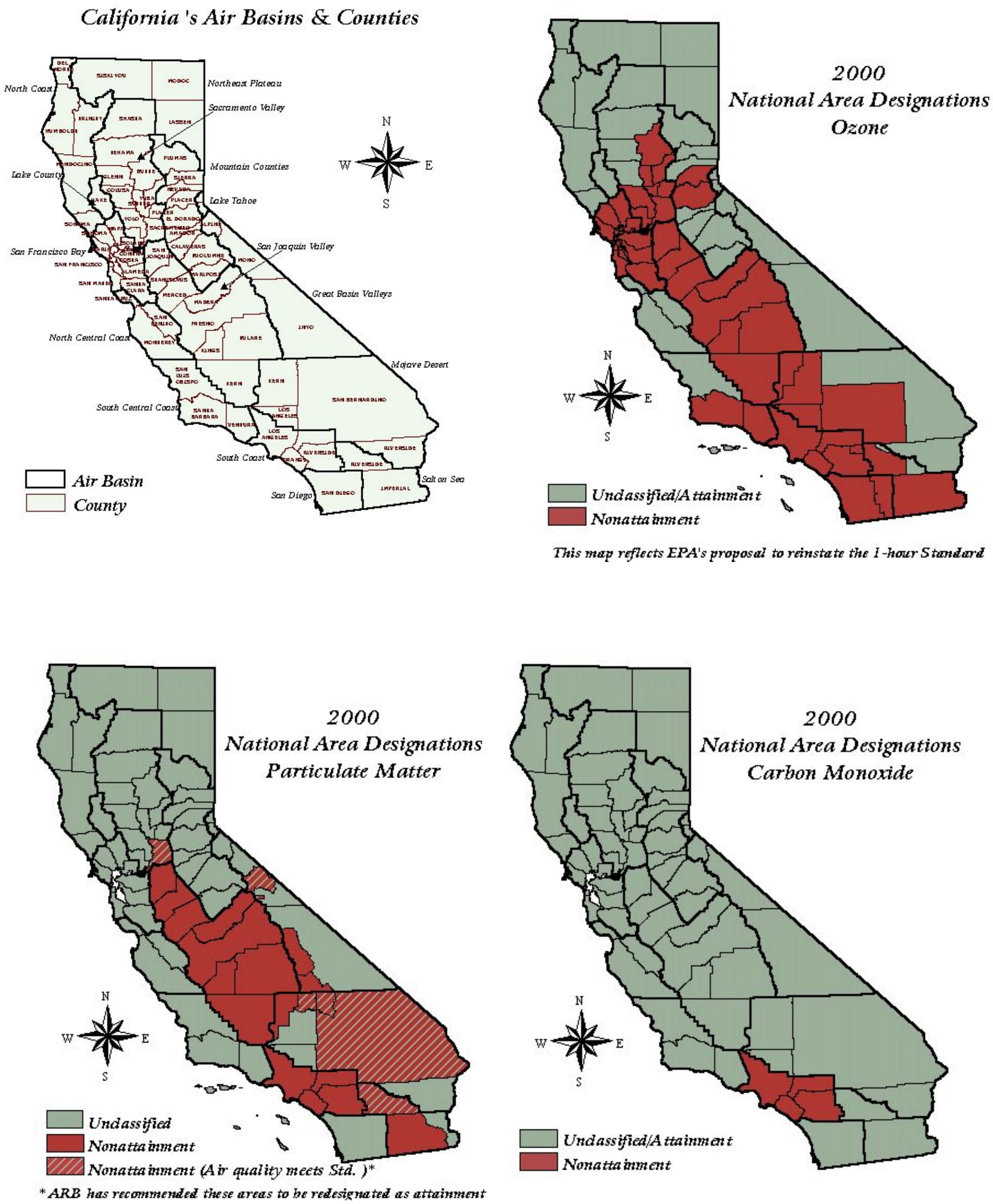

Figure 10 – California Air Basins and Attainment Designations

3.3 Standards and Regulatory Context

Natural ventilation has long been recognized by ventilation standards and building codes, though never in terms of specifying engineering-based design methods. This section discusses the standards and regulatory context relevant to natural ventilation, specifically ASHRAE Standard 62 and the California Energy Efficiency Standards (Title 24).

<u>ASHRAE Standard 62</u>

ASHRAE Standard 62-1999 currently allows natural ventilation of buildings via a short statement in Section 5.1. That section states that "Ventilating systems may be mechanical or natural. … When natural ventilation and infiltration are relied upon, sufficient ventilation shall be demonstrable. When infiltration and natural ventilation are insufficient to meet ventilation air requirements, mechanical ventilation shall be provided." The standard is not specific as to the meaning of "demonstrable" or "sufficient ventilation." An official interpretation of the standard, issued as Interpretation #8 in 1993 (reissued as #16 in 2000), states that the ventilation requirements associated with the standard's Ventilation Rate Procedure (i.e., Table 2) is not the only acceptable means of realizing such demonstration. The interpretation refers to calculation methods in the ASHRAE Fundamentals Handbook and opening area requirements in building codes. Therefore, it is not clear whether natural ventilation systems need to provide the same ventilation rates as those required by the standard for mechanical systems. The noted interpretation implies that natural ventilation systems need not provide these rates, but the standard is not very clear about this exception.

ASHRAE Standard 62-1999 has been under revision since 1997 when it was converted to continuous maintenance. Since then a number of discrete modifications or addenda have been developed that revise specific portions of the standard. Several have been approved (none of which address natural ventilation), and a number are still under development. Addendum 62j, which specifically addresses natural ventilation, is one such addendum, but it has only recently been approved for publication.

Addendum 62j attempts to partially clarify the standard's requirements with respect to natural ventilation. This addendum still allows natural ventilation systems in lieu of or in conjunction with mechanical systems. For natural ventilation systems, it contains the following requirements:

> Naturally ventilated spaces shall be permanently open to and within 8 m (25 ft) of operable wall or roof openings to the outdoors.
>
> The openable area of these openings shall be a minimum of 4 % of the net occupiable floor area.
>
> The means to open required operable openings shall be readily accessible to building occupants whenever the space is occupied.

The addendum allows for "engineered natural ventilation systems" that do not necessarily meet these requirements, but the authority having jurisdiction must approve them. The requirement for operable opening areas based on floor area is in fact consistent with most building codes.

ASHRAE Standard 62-1999 also addresses the acceptability of outdoor air quality, which is certainly relevant to natural as well as mechanical ventilation systems. The standard currently requires that outdoor air quality be evaluated by the following three-step procedure:

1. Determine if the area in which the building is located meets the EPA NAAQS (National Ambient Air Quality Standards) or equivalent state or local environmental protection authorities. Alternatively, the building is located in a community similar in population, geographic and meteorological settings and similar in industrial patterns to a community

having acceptable ambient air quality as determined by authorities having jurisdiction. Or the building is in a community with a population of less than 20,000 people, and the air is not influenced by one or more sources of substantial ambient air pollution. Or air monitoring for three consecutive months shows that the air quality meets the EPA NAAQS.

2. Determine if the outdoor air contains other contaminants, not contained in the EPA NAAQS that have been identified as of concern by other authorities cognizant of air quality.
3. If after completing steps 1 and 2 there is still a reasonable expectation that the air is unacceptable, sampling shall be conducted via NIOSH procedures and the acceptability of the outdoor air quality should otherwise be evaluated.

If the ambient air quality exceeds the EPA NAAQS, the standard states that it should be cleaned, but the standard does not require such cleaning. The standard also states that if the best available technology does not remove the offending contaminants, the amount of outdoor air may be reduced during periods of poor ambient air quality, though the standard provides no detail as to the level or duration of such a reduction.

The current requirements for ambient air quality evaluation are not particularly clear as to how one complies, and therefore these requirements are the subject of two addenda under development as part of the revision of ASHRAE Standard 62. One addendum provides more specific requirements on assessing outdoor air quality, and requires air cleaning if the EPA NAAQS requirements for PM10 are violated. Another draft addendum requires cleaning if the NAAQS limits for ozone are violated, though it currently contains several exceptions that would limit the applicability of this requirement. Both of the addenda are still in the draft form and may change before they are approved.

Title 24, California's Energy Efficiency Standards for Residential and Nonresidential Buildings

Title 24, Part 6 (July 1999) discusses natural ventilation under Section 121 Requirements for Ventilation. The requirements are very similar to those discussed with reference to addendum 62j to ASHRAE Standard 62-1999. The only differences are that the openings must be within 6 m (20 ft) of the opening instead of 8 m (25 ft) and that the openings must be greater than 5 % of the floor area instead of 4 %.

The current versions of ASHRAE Standard 62-1999 and its addenda, California’s Title 24 Energy Efficiency Standards and most building codes allow the use of natural ventilation. All of the requirements are in terms of accessible openings that are sized based on 4 % to 5 % of the floor area of the ventilated space. None of these documents consider climatic conditions or ambient air quality in their requirements, though ASHRAE Standard 62 does require an assessment of outdoor air quality. While engineering-based approaches are likely to result in more reliable designs, none of the standards require their use. At the same time, they do not disallow them.

4. Design and Analysis of Natural Ventilation Systems

This section discusses the design and analysis of natural ventilation systems. It begins with a discussion of past and current design approaches employed in the U.S., and then presents a general design methodology based largely on methods implemented in the European building community, in particular, the methodology presented by CIBSE in *Applications Manual AM10: 1997 - Natural ventilation in non-domestic buildings* [Irving andy Uys 1997]. This and other similar design methodologies have emerged from the European building communities in recent years to meet the greater demands now placed on natural ventilation systems to provide thermal comfort and acceptable indoor air quality while conserving nonrenewable energy. These ‘first generation’ analytical design methods were developed to replace the largely empirical approaches used in the past, which are still prevalent in the U.S. The approaches being employed in Europe are presently being replaced by the development of ‘second generation’ design methods to support the development of hybrid natural and mechanical ventilation systems – again methods that not only include physical design strategies but analytical tools to support the design development and design evaluation of systems utilizing these strategies. Following the general design methodology, a summary of current design and analysis tools is presented followed by a plan to develop design tools in future phases of this project. Additional design and analysis methods development needs are discussed at the end of this section.

The current state of natural ventilation design in U.S. commercial buildings can be viewed as embodying two approaches, one based on long-standing building code requirements and the other reflecting a more recent emphasis on operable windows as a means of providing improved indoor environments and saving energy. The first approach, referred to in an earlier section of this report, is based on building code requirements of a specific fraction (generally 4 % or 5%) of operable vent area relative to the occupiable floor area. This requirement has existed for decades and has been assumed by many to provide adequate ventilation and has resulted in the provision of no mechanical ventilation in many commercial buildings, particularly smaller buildings. This “code-based” approach neglects the issue of whether these operable vents or windows are actually open, how much ventilation they provide under various weather conditions and their ability to distribute ventilation to all portions of the occupied space. More recently, partly in conjunction with the interest in so-called “green” or “sustainable” buildings, there has been a renewed interest in natural ventilation for the reasons noted above (e.g., improved indoor environments and energy savings). A number of buildings have been designed and built employing features intended to provide improved energy efficiency and indoor environmental quality. Many of these buildings have employed some form of natural ventilation ranging from simply operable windows to more advanced concepts such as ventilation shafts and clerestories. However, few if any, of these natural ventilation systems are designed based on engineering considerations of the driving forces due to weather or of the resultant ventilation rates or air distribution patterns. In order to bring natural ventilation technology more in line with other aspects of building system design and to ensure that natural ventilation systems perform adequately, it is important that sound, engineering-based design methods are developed and employed.

4.1 General Design Methodology

The following is presented as a comprehensive methodology aimed at providing sound, engineering-based design methods for naturally ventilated buildings. The method presented here has been implemented in the European building community. CIBSE’s *Good Practice Guide 237* [CIBSE 1998] boils down the design of natural ventilation systems, presented in CIBSE AM10 [Irving and Uys 1997], to an eight-step process.

1. Develop design requirements
2. Plan airflow paths
3. Identify building uses and features that might require special attention
4. Determine ventilation requirements
5. Estimate external driving pressures
6. Select types of ventilation devices
7. Size ventilation devices
8. Analyze the design

Develop design requirements – This step consists of establishing design requirements against which the success of a building design can be measured. This step should also establish, early on, whether or not the option of implementing natural ventilation is viable from both a practical and economic perspective. Consideration should be given to the indoor environmental requirements with respect to internal heat gains, air quality and humidity; space requirements; prevailing and extreme weather conditions; ambient pollutant levels; and construction and operating costs.

Plan airflow paths – This step consists of selecting the overall type of natural ventilation strategy to use. It requires the establishment of airflow paths of the outdoor air into the occupied spaces of the building and then out through planned exhaust locations. Consideration must be given to the orientation of the building to prevailing winds, surrounding terrain and obstructions; external pollutant sources; and potential stack flows. Consideration should also be given to implementing mechanically assisted and mixed-mode ventilation strategies as well as the use of night cooling of the building thermal mass.

Identify building uses and features that might require special attention – This step requires the designer to consider issues that might affect the behavior or effectiveness of a natural ventilation system. Issues include the presence of relatively large heat gains, internal obstructions to airflow, indoor and outdoor pollutant sources, envelope leakage characteristics, and acoustic isolation.

Determine ventilation requirements – This step requires the designer to determine the airflow rates required to satisfy the previously determined design requirements. As previously described, ventilation is provided for four basic purposes including air quality control, direct cooling (advective and personal) and indirect night cooling. Ventilation for air quality control typically establishes minimum ventilation rates based on existing ventilation standards and building codes. Weather data and internal loads are used to determine required flow rates during the different seasons of the year for both direct and indirect cooling purposes. This step should highlight circumstances that may lead to excessive heat gain that could reduce the likelihood of cooling by natural means. These circumstances will either require modifications to design building configuration (e.g. shading to reduce solar gain) or indicate when and how much mechanical ventilation and conditioning might be required (e.g., to overcome insufficient driving forces or extreme climatic conditions).

Estimate external driving pressures – This step requires the designer to select or determine the driving forces to which the building is likely to be subjected including wind and stack-induced and to determine the design conditions to be used in selecting and sizing the ventilation devices. If detailed analysis is to be performed, then detailed weather data will be needed. This could be in the form of measured data or other available design weather data (e.g. WYEC2, TMY2, etc.).

Select types of ventilation devices – This step requires the designer to identify the locations in the previously planned airflow paths at which ventilation devices will be required and the types of devices that will be used in those locations. The locations are typically inlets and outlets through the building envelope and openings within the space through which ventilation air is intended to flow. Ventilation devices include windows, trickle vents, exhaust stacks, louvers and doorways, and mechanical assist fans. The flow characteristics of these devices must also be identified. These characteristics typically consist of relationships between the airflow rate through the device and the pressure difference across it.

Size ventilation devices – This step requires the designer to determine the size of the ventilation devices that were selected in the previous step. Sizing can be performed using either explicit or implicit methods. Explicit methods are based on equations relating driving forces (e.g., wind and stack-driven flows) to airflow characteristics and sizes of the ventilation devices. Implicit methods require sizes of the ventilation devices to be used to determine airflow through them, so this process is often an iterative one in which the designer selects from available devices, analyzes their effectiveness in meeting design ventilation requirements, and iteratively selects devices until a viable solution is obtained. The use of sizing methods and tools can be very helpful in minimizing or even eliminating the iterations depending on the complexity of the design. The sizing of ventilation devices can be complicated by a potentially large number of unknown design parameters. Therefore, this process requires sound engineering judgment in providing additional design constraints to see the sizing process to fruition.

Analyze the design – This step requires the designer to thoroughly evaluate the design for its effectiveness in providing ventilation rates to meet the design requirements. This includes evaluating the design under various weather conditions and heat loads, determining potential situations where design goals might not be met, evaluating the effects of "unintentional" envelope leakage, and evaluating the potential "misuse" of occupant-controlled ventilation devices. The use of analysis tools can be very beneficial here to provide detailed simulations of the behavior of the building design including airflow rates, pressure relationships between zones, contaminant/exposure information, temperatures, and energy use.

4.2 Natural Ventilation Analysis and Design Tools

This section presents a summary of the currently available tools for designing and analyzing natural ventilation systems. In this discussion, *analysis* refers to the process of predicting building response given building system characteristics and driving forces (i.e., wind, buoyancy, and mechanical driving forces) while *design* refers to the inverse problem of determining building system characteristics (e.g., the size of a ventilation opening) given desired building response – the *design requirements* – and expected driving forces. Mathematical *models*, based on physical idealizations of building systems often represented by diagrammatic *models*, are necessarily common to both analysis and design *tools*. Two broad classes of models may be distinguished:

- *macroscopic* models (e.g., multi-zone building models) based on physical idealizations of building systems as collections of control volumes whose behavior may be described by algebraic or ordinary differential equations, and
- *microscopic* models (e.g., computational fluid dynamics or CFD models) based on numerically approximate solutions of systems of partial differential equations (e.g., the Navier-Stokes equations for fluid flow) wherein the physical domain of the "system" is subdivided into a relatively fine mesh.

As analysis tools may be used in an iterative, trial and error manner to search for acceptable building characteristics, the distinction between a design and analysis tool is not often made. In this discussion, however, a sharp distinction will be maintained.

The focus of this discussion is on tools that incorporate a macro-model of buildings (e.g. single-zone and multi-zone tools) as opposed to a micro-model as implemented by CFD tools. There are several limiting factors that render CFD impractical as a ventilation design tool including the fact that CFD cannot be applied to a whole building, the difficulty in establishing boundary conditions and the large computational and personnel cost involved in implementing CFD even for more manageable projects. This is not to say that CFD analysis tools are not useful in the design process; they can be very beneficial in analyzing temperature, airflow and contaminant fields within individual zones of a building, particularly within large spaces such as atria.

Existing Analysis Methods and Tools

Depending on design requirements, analysis of natural ventilation systems will require consideration of energy, airflow (due to both natural and mechanical driving forces), and contaminant transport. The complex interaction between these coupled characteristics makes it difficult to fully address them all in a single, generally applicable method or tool. This has led to the development of a wide range of different analysis tools to address these characteristics in varying levels of detail and often on an individual basis. Analysis tools typically fall into three basic categories of single-zone, multi-zone or computational fluid dynamics.

Single-zone models consider the entire building to consist of a single volume of well-mixed air with no internal partitions. Envelope penetrations can be defined in varying levels of detail depending on the model. Penetrations can be further defined to include intentional flow paths as well as unintentional leakage paths and can be distributed vertically along the façade. Consideration can be given to wind, buoyancy, or both effects on the airflow through the paths. Some methods also account for thermal characteristics of the building envelope and structure, for example the NatVent program [Orme 1999]. Single-zone models are generally good for first-cut calculations, but are not as useful as multi-zone analysis, because inter-zonal airflow paths are not accounted for. They can also be useful in performing quick comparisons between different building configurations but with uncertain accuracy and even correctness [Allard 1998].

Multi-zone models can be used to describe a building as a set of zones that are interconnected by airflow paths. The zones are typically well-mixed, i.e., the air within the zone is considered to be at the same state throughout the zone at any given time (e.g. temperature, pressure and contaminant concentration). These models can provide much greater detail than their single-zone counter parts, as commonly configured, and can be used to perform single-zone analysis as well. The more advanced models can require a fair amount of detailed input depending on the complexity of the building representation being implemented. There are several multi-zone modeling software tools now available both commercially and in the public domain that provide very flexible handling of airflow and contaminant transport, including mechanically induced airflows, such as CONTAM, COMIS, and BREEZE [Orme 1999]. These tools provide the ability to perform steady-state as well as transient (quasi-steady) analysis that enable simulations up to a year, including the use of design or measured weather data.

While the aforementioned multi-zone analysis tools are very useful for isothermal conditions, they generally lack the heat transfer analysis capabilities that would prove quite useful in the analysis of natural ventilation systems. There are other programs available that handle the heat transfer aspects of building analysis such as EnergyPlus/DOE-2, ESP-r, AIOLOS and IDA ICE [Crawley, et al. 2000, Leal 2000, Allard 1998, Bring, et al. 1999]. These typically don't handle the airflow and contaminant transport analysis like the multi-zone modeling tools. The DOE-2 energy analysis program only handles non-HVAC system airflows in the form of user input envelope infiltration rates. Given, these leakage rates, the program calculates the energy requirements to condition the infiltration air, but doesn't account for differences in these leakage rates due to buoyancy and wind driven effects. The multi-zone analysis tools, COMIS and CONTAM, have been integrated with another thermal analysis tool, TRNSYS. TRNSYS is a modular environment that enables independently developed modules to be integrated into an already very powerful analysis system. COMIS and CONTAM modules have been created and implemented within the TRNSYS environment to enable the analysis of the energy requirements due to air infiltration [Dorer and Weber 1994, Dols and Walton 2000].

Existing Design Methods and Tools

The eight-step process presented in section 4.1 provides a general approach to designing natural ventilation systems. It will be presented here as the "process of choice" while recognizing that other design approaches could be applied as well. The eight-step process often occurs in three distinct phases:

- Conceptual Design – steps 1, 2, 3, and 4,
- Design Development – steps 5, 6, and 7, and
- Design Performance Evaluation – step 8.

The following presents a brief review of existing methods associated with these phases of the process. Details of outdated empirical methods are left out, but references are provided to more detailed presentations of these methods.

Conceptual Design

A series of international European research programs supported in part by the International Energy Agency, building on the earlier work of the British Research Establishment, have led to the development of a number of publications that provide general guidelines and some rules of thumb to aide the designer in the conceptual design phase [Allard 1998, Irving and Uys 1997, CIBSE 1998, Petherbridge, et al. 1988, BRE 1999, and BRE 1994]. For example, the BRE Digest *Natural Ventilation in Non-domestic Buildings* suggests single-sided ventilation schemes be limited to rooms with sectional widths no greater than 2.5 times their ceiling heights and operable window areas approximately equal to 5 % of the room floor area. For wind-driven cross ventilation, on the other hand, this Digest suggests sectional widths can be as much as 5 times the ceiling height.

As new design strategies have been put forward, including more ambitious uses of night cooling and, most recently, hybrid combinations of natural and mechanical ventilation, these publications and especially the rules of thumb contained within them have quickly become dated. Nevertheless, the more general fundamental strategies presented remain valid and the associated guidelines useful.

Design Development

A variety of tools for use in the design development phase have been published over the years including:

- sizing rules of thumb,
- non-dimensional design graphs based either on fundamental theory or correlation studies using more detailed simulation tools,

- spreadsheet programs,
- specialized simulation programs intended to be used iteratively to search for acceptable ventilation component sizes,
- general purpose airflow simulation programs also used iteratively, and
- analytical methods used to determine component sizes more directly given a specification of design requirements and environmental conditions.

For general reviews of these tools, see Li, et al. [999], Allard [1998], and Orme [2000].

The simpler tools are invariably based on single zone models of building systems that ignore internal resistances to airflow and seldom account completely for the coupled thermal airflow interactions that are characteristic of natural ventilation airflow systems. In principal, the former shortcoming can be accepted because, properly, internal resistances to airflow should be minimized by design. However, without supporting analysis, the designer may not know whether this objective has been realized. In some wind-driven natural ventilation systems the coupled thermal airflow interactions may not be critical, but in most systems, especially when used for cooling, all of these interactions are important and must be considered.

In developing tools to directly size ventilation components given design requirements and environmental conditions two types of design problems may be distinguished. A so-called ‘first-order’ design problem is one wherein design requirements are defined in terms of required ventilation rates while a ‘second-order’ design problem is defined in terms of either thermal or air quality design requirements. Suffice to say, ‘first-order’ design problems are more readily defined and solved than ‘second order’ problems; indeed most design is approached as a ‘first order’ problem whether approached directly or iteratively.

Axley has presented a general approach to the ‘first-order’ design problem that is based on the same theory currently used in multi-zone airflow analysis programs like CONTAM and COMIS. This method is based on accounting for pressure changes that must occur in ventilation “loops” formed by following a ventilation flow path from inlet to exhaust and back to the inlet again. The “pressure loop method” allows for direct sizing of airflow components, accounts for both buoyancy (stack) and wind-induced airflow, and can be applied to multi-zone building idealizations to account for internal resistances to airflow such as doorways and transoms. Furthermore, this approach may be applied using statistical representations of environmental conditions for specific locations to better account for local environmental impacts. The method may be applied manually or, since it shares the same theoretical base, it may be implemented within the interface of existing multi-zone programs [Axley 2001a].

The pressure loop component sizing method is based on the macroscopic multi-zone view of a building and includes the interconnection between zones represented by pressure-flow relationships. These pressure-flow relationships are typical of those found in existing multi-zone analysis tools and include power law, effective leakage area, orifice, quadratic, self-regulating, duct and fan components. While the analysis tools require the user to define the physical characteristics of these flow components and then calculates the airflow rates through them, the sizing method requires the user to define the design airflow rates through the components and determines the physical characteristics of the components to provide the required flow rates.

The following is an outline of the *Loop Equation Design Method*.

1. Layout the global geometry and multi-zone topology of the passive ventilation flow loops for each zone within the building.
2. Identify an ambient pressure node and additional pressure nodes at entries and exits of each flow component along the loops.
3. Establish design conditions: wind pressure coefficients for envelope flow components, ambient temperature, wind speed and direction, interior temperatures, and evaluate ambient and interior air densities.
4. Establish first-order design criteria (i.e., a ventilation objective) and apply continuity to determine the objective design airflow rates required for each passive ventilation flow component.
5. Form the forward loop equations for each loop established in Step 1 above by systematically accounting for all pressure changes while traversing the loop.
6. Determine the minimum feasible sizes for each of the flow components by evaluating asymptotic limits of the loop equation for the with-wind and without-wind cases separately.
7. Develop and apply a sufficient number of technical or non-technical design rules or constraints to transform the under-determined design problem defined by each loop equation into a determined problem.
8. Develop an appropriate operational strategy to accommodate the regulation of the passive ventilation system for variations in design conditions.

Examples of the application of this method to both residential and non-residential buildings are presented in Axley (2001a, 2000a, 2000b, 1999a and 1999b). The method can, with difficulty, be done by hand or, more readily, be carried out using spreadsheet or symbolic mathematical analysis software.

In the example diagram shown in Figure 11, based on the Inland Revenue building, England [Irving and Uys 1997], three loops are relevant. For the upper loop passing through the ambient pressure node 13 to the surface node 14 and on through nodes 15, 18, 19, 20, and 21 back to node 13, the accumulated pressure differences due to wind from 13 to 14 plus those due to flow through inlet vent “e”, the buoyancy change from 15 to 18, flow through exhaust “g”, and the buoyancy changes from 18 to 20 and from 20 back to 13 must, necessarily, sum to zero. The wind-driven pressure changes are determined by given approach wind velocity and characteristic wind pressure coefficients for the building form and the buoyancy pressure changes depend on given zone and outdoor air temperatures thus leaving the pressure drops in the discrete flow components to be the only unknows. Given required ventilation rates, then, the pressure drops in these flow components may be directly related to the component size characteristics (e.g., opening area of the inlet, cross-sectional area and height of the stack, etc.). The pressure loop equations, thus, link the environmental conditions (i.e., wind speed and direction and assumed temperatures) and design requirements directly to ventilation system component sizes. Thus these loop equations may be used to directly size these components [Axley 2001b].

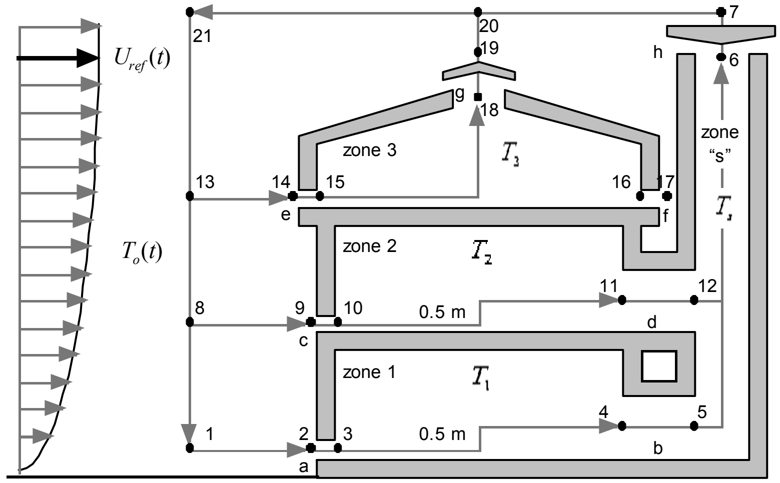

Figure 11 Sample Diagram Displaying Pressure Loops

The "loop method," in its current formulation, is based on multi-zone airflow analysis theory that assumes, in effect, steady conditions of airflow prevail. It, therefore, does not account for unsteady airflow phenomena nor does it account directly for unsteady coupled airflow and thermal interactions. The former shortcoming is commonly believed to be minor, although due to this shortcoming the application of the loop method to single-sided ventilation and backdrafting phenomena would be misguided. The later shortcoming is likely to be more important as the "loop method's" application to the important night cooling natural ventilation strategy is very limited. The extension of the method to night cooling and other ventilation strategies where the coupled thermal airflow interactions need to be more faithfully considered is, however, not out of the question and should be considered.

<u>Design Performance Evaluation</u>

Increasingly stringent air quality and energy efficiency demands have made design performance evaluation critical to the success of natural ventilation systems. This involves the simulation of the performance of the proposed building system to evaluate both the temporal and spatial variation of air quality and thermal comfort provided and the energy consumption required (e.g., to condition ventilation air). Given the need for spatial and temporal detail, multi-zone airflow analysis tools have become the method of choice for performance evaluation. Here, again, it would be best to use multi-zone analysis tools that account for the coupled thermal airflow interactions yet these tools demand further development before they may reasonably be applied in practice.

4.3 Plan for Analysis and Design Tools

As previously stated, the design of natural ventilation systems is currently accomplished by iteratively applying analysis tools until design requirements are satisfied. The reasons for this relate to the very complex nature of building design itself, i.e., there is perhaps an infinite set of design possibilities. The trick is to narrow the focus of design to attack a manageable subset of the possibilities and to implement engineering judgment to identify and satisfy design requirements. While it is very unlikely that the need for analysis tools can be completely eliminated at this time, tools that can minimize the iteration process are needed to assist the design engineer in narrowing their focus. This section presents a general outline of plans to develop both design and analysis tools for natural ventilation systems including a design tool based upon the *Loop Equation Design Method*.

Design Tools

In terms of natural ventilation design tools, one such tool is the *Loop Equation Design Method* presented above. This tool appears to be a promising method for sizing of natural ventilation components due to its generality, practicality and direct consideration of stack and wind-driven airflow that is critical in addressing natural ventilation airflow. The method can even be used to address infiltration and mechanically assisted airflow that is essential in considering the design of hybrid ventilation systems. As indicated, the method has been presented as a "paper" method that would greatly benefit from being implemented within existing building analysis tools. This implementation could provide a method of visualizing and defining pressure loops, relieve the designer of the burden of forming and solving the proper equations, provide a seamless transition into the analysis phase of design, and even provide a method of documenting the design process.

A tool to implement the *Loop Equation Design Method* should provide the user with the means to perform the eight steps presented above. Because proper implementation of the method requires engineering judgment, the tool should also provide significant guidance in applying that judgment. Multi-zone modeling tools typically provide most of the capabilities called for in items 1 through 3 including establishing the global geometry and topology of zones and interconnecting flow paths, specifying an ambient pressure node and intrinsically the inlet and outlet pressure nodes of airflow components, and establishing the design conditions. Specification of the ventilation flow loops is the main and non-trivial requirement needed in these tools. Step 4 is a relatively simple matter of providing a means of defining airflow components as natural ventilation design types and allowing for the input of a first-order design requirement. The tool could also be made to calculate component-specific requirements from more general requirements such air changes per hour. Steps 5 through 6 comprise the main computational portion of the method and are fairly straightforward in terms of setting up the representative loop equations based on the "design" form of the airflow components (i.e. the inverse of the analysis form). However, Step 7 will likely require a significant amount of user-interaction to impose design constraints, and could prove to be a very challenging aspect of implementing the method with minimum burden to the user. Depending on the design constraints (e.g. multiple-loop constraints), there is a potential for the need to solve a relatively difficult set of nonlinear equations. Providing detailed guidance would likely prove to be very beneficial to the user. Step 8 entails consideration of how to operate ventilation systems to maintain design requirements under conditions other than the extreme design cases by perhaps varying inlet and outlet damper positions or implementing mechanical assistance. This step might also entail a more detailed analysis of the design for annual weather patterns to determine the extent to which design requirements are exceeded or under-achieved.

Analysis Tools

The needs for analysis tools are broken down here into immediate needs and those that are less immediate and should be considered for future implementation. The immediate needs are those that will provide support for analysis of ventilation components described in Axley (2000a), such as self-regulating vents and the numerical methods to handle them. The less immediate needs are those that would further the treatment of phenomenon that are not typically addressed in multi-zone airflow analysis tools yet are very important to the analysis of natural ventilation systems. These needs include the treatment of heat transfer, non-trace contaminants such as moisture, and building controls. These are discussed later in this report in the section on *Additional Development and Opportunities.*

Development Plans for Next Phase of this Project

Based on the previous discussion of natural ventilation design and analysis, it appears that the most feasible plan would be to implement the *Loop Design Method* within an existing multi-zone simulation environment. This would greatly leverage existing multi-zone analysis capabilities and also provide a relatively seamless transition between design and analysis stages of the design process. It is also proposed that a pre-design tool be developed based upon the *climate suitability analysis*, presented earlier, to simplify the process of evaluating the potential application of natural ventilation to various climates.

DESIGN TOOLS

Two design tools are proposed for development – one to implement the climate suitability method and another to implement the Loop Design Method. The climate suitability tool would provide preliminary estimates of the ventilation rates needed to achieve direct cooling for a variety of internal gain levels and the minimum night cooling ventilation rate that would be required to offset internal gains of the following day. This would lead to the following four-step design process:

- Step 1: use climate suitability results for your climate to determine preliminary required daytime and night time ventilation rates
- Step 2: layout global geometry and topology following CIBSE guidelines or using one of many built precedents
- Step 3: use *Loop Design Method* to get preliminary sizes of all components and establish primitive aspects of operation/control strategy.
- Step 4: use annual analysis to evaluate the performance of the now specified system and iteratively refine design (e.g., component sizes and possibly global geometry and topology) and control strategy.

It is proposed that the *Loop Design Method* be implemented within the existing multi-zone analysis environment of CONTAM [Dols et al. 2000]. CONTAM is a public domain program that provides users with an intuitive graphic interface to develop models, or graphic idealizations, of specific building ventilation system proposals. It currently provides an interface that could be used to implement steps 1 through 4 of the loop method as described above. The specifics of how to implement the method need to be worked out, but the following presentation indicates the tasks and issues that should be addressed.

A. Develop loop selection interface – This would provide the user with the means to identify specific ventilation loops and assign airflow component types to these loops. Presently, the CONTAM interface provides the user with the tools to create schematic plan diagrams of building airflow systems by drawing floor plans and placing airflow component icons on a graphic "sketchpad." To implement the loop method within the CONTAM interface, the user would have to additionally identify specific ventilation loops for investigation and component sizing. This could be as simple as providing another input parameter for each airflow component designating loop numbers of which the flow component is a member or by allowing the user to link airflow components graphically to define specific loops. It would be desirable to provide validation of the component sets to insure that they do actually form closed loops. This could be done either programmatically, or visually by providing the user with an elevation view of a building cross-section and displaying the loops on this view. Alternatively, graph theoretical methods are available that could be used to identify all independent ventilation loops that then could be presented to the user for selection for subsequent design development – reasonably a 'second generation' approach to implementation.

B. Develop inverse airflow components – CONTAM airflow component equations are formulated in the so-called "forward" form while the loop method uses these same equations in "inverse form" – a form relating the pressure drop across components to the volumetric (or mass) flow rate and characteristic design variables (e.g. characteristic duct cross-section and height dimensions for a stack or a threshold flow rate for a self-regulating vent). Most, but not all, CONTAM component equations have been transformed to inverse form for use in the loop method [Axley 2001]. The remaining component equations will need to be transformed and a small number of additional flow component relations will need to be added to the CONTAM library of components (e.g., self-regulating vents and stack terminal devices).

C. Develop loop equation assembler routines – Computational routines will be needed to form the loop equations based upon the user-defined loops, inverse flow components types, and relevant design conditions including design airflow rates, indoor and ambient air temperatures, wind speed and direction, and relative component height. These routines do not actually solve the loop equations, rather they accumulate the numerically determined pressure changes that occur when progressing around any given loop that are needed to evaluate asymptotic limits on component sizes (i.e., characteristic design variables). These numerically determined pressure changes result from wind and buoyancy effects and, importantly, pressure drops across individual components whose sizes have been fixed in the design development process.

D. Develop asymptotic limit evaluation routines – At any stage in design development (i.e., as the user systematically fixes component sizes) the results of loop equation assembly may be used to determine limiting sizes of the remaining airflow components of each loop. Computational routines will have to be developed, most reasonably as procedure calls to the component routines currently available in CONTAM, to compute these limits and to present these limits to the user. In most cases this will involve rather trivial algebraic routines. In a few cases, however, implicit methods may have to be used to evaluate these limits. This is not expected to be particularly problematic.

E. Develop design development iteration interface – Design development will involve the iterative repetition of the routines developed in Task *B* and *D* as the designer systematically fixes sizes of specific components. This not only recognizes the fact that a variety of acceptable design solutions can be formulated, but allows the user/designer to impose practical design constraints on the selection process (e.g., due to discrete available component sizes or simply preferences related to architectural considerations such as preferred window sizes). This interface should also allow the simultaneous consideration of multiple environmental states – typically for low wind and average wind conditions for two or more seasons – so that the designer can also develop operational strategies in parallel. A typical example here would be the specification of a self-regulating vent setting for winter and summer conditions.

ANALYSIS TOOLS

The more immediate needs for analysis tools include the implementation of airflow components that have been developed specifically for implementation in natural ventilation systems. Specifically, the self-regulating vent should be implemented. Models of this component are known to lead to numerical instability in the current solver of CONTAM. Thus the development of the important self-regulating component models will demand the collateral development of an improved, more robust solver. Lorenzetti has developed a number of solution strategies that have demonstrated promising results in trial runs within the CONTAM environment [Lorenzetti 1999a, 1999b, 1999c, 2000]. Consequently the development of improved solvers appears to be quite feasible and perhaps extendable to a more general set of airflow components. This would also provide an increased capability to handle components that have yet to be developed.

4.4 Additional Developments and Opportunities

This section presents additional capabilities and opportunities for promoting the design and analysis of naturally ventilated buildings in the U.S. that would serve to improve analysis and design capabilities of existing and proposed methods and tools. A list of proposed analysis capabilities is presented as well as a proposal to organize meetings to promote the practice of designing naturally ventilated buildings in the U.S.

Coupled Thermal-Airflow Analysis

The need to couple heat transfer with multi-zone airflow modeling capabilities has been recognized for some time. Thermal and airflow interactions are characteristic of natural ventilation airflow systems. Indeed, leading researchers in the field state emphatically and unequivocally that the practical design of natural and hybrid ventilation systems demands analysis of these coupled interactions.

Efforts are underway on several fronts to perform this integration. However, numerical problems of stability, convergence, and solution multiplicity have yet to be completely resolved when performing this integration. Hence, in order to implement this integration or coupling of thermal and airflow analysis, trade-offs are often made in the “tightness of coupling” [Woloszyn 2000].

An unreleased research version of the CONTAM family of programs, designated internally as CONTAM97R, has been recently used in modeling studies of a six story Dutch Tax Office building in a number of U.S. climates. Initial comparisons of measured and predicted building performance are not only encouraging but clearly demonstrate the critical need for such complete modeling (Axley 2001b).

Non-trace “Contaminant” Analysis

Multi-zone analysis tools typically provide airflow and contaminant dispersal analysis (i.e., for air quality evaluation). Without exception, available contaminant dispersal analysis tools assume air contaminants exist at trace levels and, thus, do not influence the buoyancy of the airflow. Recent interest in so-called “evaporative down-draught chimneys” wherein a water spray is used to evaporatively cool and induce downward airflow in inlet chimneys and thereby force warmer air out of exhaust chimneys has forced the need for non-trace “contaminant” analysis (i.e., treating water vapor content as a “contaminant”). This particular natural ventilation cooling strategy is based on ancient Middle Eastern precedents and, in its technically more developed versions, appears to be a very attractive strategy for hot arid urban environments. Again, the research version of CONTAM – CONTAM97R – includes non-trace analysis capabilities based on fundamental theory but these capabilities have yet to be studied systematically for purposes of validation and practical application.

Dynamic Control of Ventilation Systems

While considerable and important progress in passive strategies of controlling natural ventilation systems has been achieved in the past decade, it is now clear that passive control devices – most notably self-regulating vents – may be complemented by active control of system settings. Furthermore, the improved performance demonstrated by very recent hybrid ventilation systems that necessarily demand active control places an even greater need on the development of modeling tools to simulate active control of ventilation systems. Yet again, the internal research version of CONTAM – CONTAM97R – includes control analysis capabilities but these capabilities have yet to be studied systematically for purposes of validation and practical application.

All of the aforementioned capabilities have been addressed to varying degrees, and some would be more readily adapted into current analysis environments. Addressing these issues individually is critical in developing the techniques, but an integrated design and analysis environment would greatly benefit designers of natural ventilation systems. This environment should be as simple to use as possible, but the complex nature of the problems addressed with these tools can only be simplified so much without compromising their general applicability. This is why multi-zone analysis is proving to be beneficial, because it greatly reduces the complexity of the building systems while maintaining the level of sophistication necessary to capture the overall nature of building behavior.

Design Symposia and Workshops

Innovation in natural and hybrid ventilation systems is being driven in Europe largely by aggressive and forward looking professional design firms. In a very real sense, their efforts are outpacing research in the field and, as a result, are setting research agendas. Recognizing the need to communicate new ideas within the profession these European design professionals – often identified as "building environmental engineers" – have organized a number of symposia. Perhaps foremost among these symposia is the Intelligent Building Design symposia held annually for the last six decades with the most recent symposium organized by TRANSSOLAR Energietechnik GmbH of Stuttgart.

Similar symposia could be mounted in the U.S. This would most reasonably be done early-on by selecting the most innovative presentations from the European symposia and inviting the presenters to participate in a regional or national symposium in the U.S. To take full advantage of the specialized knowledge these practitioners currently have, design workshops should be organized to complement such a symposium.

5. Summary

Natural ventilation offers the means to control air quality in buildings, to directly condition indoor air with cooler outdoor air, to indirectly condition indoor air by night cooling of building thermal mass, and to provide refreshing airflow past occupants when desired. When compared to mechanical ventilation alternatives and depending on climate and other factors, natural ventilation systems can reduce first and energy costs, recover the valuable building space typically used by all-air mechanical systems, potentially provide health, comfort, and productivity advantages, and may offer users greater control of their environments leading to less restrictive comfort criteria. Yet natural ventilation systems presently lack proven ventilation heat recovery and filtration capabilities, are generally difficult to control and are inherently unreliable when natural driving forces are small. The key to overcoming these shortcomings and realizing the potential advantages of natural ventilation is the emergence of hybrid natural and mechanical system strategies.

Three important considerations specific to the application of natural ventilation to commercial buildings in California are climate suitability, ambient air quality, and relevant codes and standards. A new ventilative cooling metric was described and used to demonstrate that the coastal climates of California are potentially very well-suited to natural ventilation. The hotter, inland locations are less suited to a simple natural ventilation strategy but may be able to benefit from night cooling or hybrid system strategies. A review of ambient air quality data indicates that much of California fails to meet the national standards for one or more contaminant. However, since ambient air quality problems may vary by season, time-of-day, and locality, natural ventilation strategies may still be considered acceptable at all times in some areas and part of the time in other areas through innovative hybrid systems. While relevant national, state, and local building codes and standards allow natural ventilation in commercial buildings, they provide minimal guidance on acceptable application. Again, hybrid systems may eventually be more acceptable due to greater assurance that sufficient ventilation rates can be maintained at all times.

Finally, there is a lack of proven, fundamental-based tools and processes for design and analysis of natural ventilation systems in commercial buildings. A plan developing new design and analysis guidance and tools is described.

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7. References

Allard F. (Ed.) (1998) *Natural Ventilation in Buildings; A Design Handbook* London, James and James Science Publishers Ltd.

Anon (1992). European patent application: self regulating ventilation grate. European Patent Office.

Arnold, D. (2000). Thermal Storage Case Study: Combined Building Mass and Cooling Pond. ASHRAE Transactions, 106 (1): 819-827

ASHRAE (1999). ASHRAE Standard 62-1999: Ventilation for Acceptable Indoor Air Quality. Atlanta, GA, ASHRAE.

ASHRAE (1997). 1997 ASHRAE Handbook – Fundamentals. Atlanta, GA, ASHRAE.

ASHRAE (2000). ASHRAE Handbook of HVAC Systems and Equipment: Chapter 16 Duct Construction - Duct Cleaning. Atlanta, ASHRAE.

Axley, J.W. (1999a). Natural Ventilation Design Using Loop Equations. Proceedings of Indoor Air 99, 4: 316-321.

Axley, J.W. (1999b). Passive Ventilation for Residential Air Quality Control. ASHRAE Transactions, 105 (2): 864-876.

Axley, J.W. (2000a). Design and Simulation of Natural Ventilation Systems Using Loop Equations. Proceedings of Healthy Buildings 2000, 2: 475-480.

Axley, J.W. (2000b). Zonal Models Using Loop Equations and Surface Drag Cell-to-Cell Flow Relations. in RoomVent 2000 – 7th International Conference on Air Distribution in Rooms. University of Reading, UK: Elsevier.

Axley, J.W. (2001a). AIVC Technical Note 54 – Residential Passive Ventilation Systems: Evaluation and Design. Coventry, AIVC.

Axley, J.W. (2001b). Application of Natural Ventilation for U.S. Commercial Buildings – Climate Suitability, Design Strategies & Methods, Modeling Studies. GCR 01-820, National Institute of Standards and Technology.

Berry, J. (2000). Super-Efficient Mechanical Ventilation. Indoor and Built Environment, 9 (2): 87-96.

Bradshaw, V. P. E. (1993). Building Control Systems. New York, John Wiley & Sons.

Brager, G.S. and R. de Gear (2000). A Standard for Natural Ventilation. ASHRAE Journal October 2000: 21-28.

Braham, G. D. (2000). Comparative Performance of U.K. Fabric Energy Storage Systems. ASHRAE Transactions, 106 (1): 811-818.

BRE (1994). Natural Ventilation in Non-Domestic Buildings. Building Research Establishement: Garston, Watford, UK.

BRE (1999). NatVent - CD-Rom, Building Research Establishment. 1999.

Bring, A., P. Sahlin and M. Vuolle. (1999). Models for Building Indoor Climate and Energy Simulation – A report of IEA SHC Task 22: Building Energy Analysis Tools. Stockholm, IEA.

BRECSU (2000). Energy Conusmption Guide 19: Energy Use in Offices. Garston, Watford, UK, British Research Establishment Conservation Support Unit: 23 pages.

Brodrick, J.R. and D. Westphalen (2001). "Uncovering Auxiliary Energy Use"; ASHRAE Journal, February 2001: 58-61.

CARB (2001). The 2001 California Almanac of Emissions and Air Quality. California Air Resources Board - http://www.arb.ca.gov/aqd/almanac01/pdf/almanac2001%20all.pdf.

CIBSE (1997). Natural Ventilation in Non-Domestic Buildings; Applications Manual AM10. London, Chartered Institution of Building Services Engineers CIBSE.

CIBSE (1998). Good Practice Guide 237 - Natural Ventilation in Non-Domestic Buildings; A Guide for Designers, Developers and Owners. London, Chartered Institution of Building Services Engineers.

Conte, E. and I. Fato (2000). Thermal Comfort In Mixed Mode Buildings. Healthy Building 2000, Espoo, Finland, SIT Indoor Air Information Oy, Helsinki, Finland.

Crawley, D. L.K. Lawrie, C.O. Pedersen, and F.C. Winkelmann. (2000). EnergyPlus: Energy Simulation Program. ASHRAE Journal, April 2000: 49-56.

de Gids, W. F. (1997). Controlled Air Flow Inlets. 18th AIVC Conference - Ventilation and Cooling, Athens, Greece, AIVC.

de Gids, W. F. (1999). Controlled Air Flow Inlets. London, BRE.

Dols, W.S., Walton, G.W., and K.R. Denton (2000). CONTAMW 1.0 User Manual NISTIR 6476, National Institute of Standards and Technology.

Dorer, V., A. Weber. (1994). Multizone Air Flow Model COMVEN-TRNSYS. EMPA/IEA-ECB Annex 23, Bübendorf, Switzerland.

EPA (1987). National Primary and Secondary Ambient Air Quality Standards, Code of Federal Regulations, Title 40 Part 50 (40 CFR50), as amended July 1, 1987. U.S. E.P.A.

Fisk, W. J. (1998). Improved Productivity and Health from Better Indoor Environments: Estimates of Potential National Benefits. Berkeley, CA, Lawrence Berkeley Laboratory.

Fisk, W. J. and A. H. Rosenfeld (1997). Estimates of Improved Productivity and Health from Better Indoor Environments. Indoor Air, 7: 158-172.

Gunnarsen, L. (2000). Replacing Mechanical Ventilation with Natural Ventilation and Increased User Control- An Intervention Study in a School. Healthy Buildings 2000, 2: 297-302.

Heikkinen, J. and I. Heimonen (2000). Hybrid Ventilation Expectations Among Finnish Designers and Decision Makers. Healthy Buildings 2000, 2: 511-516.

Heiselberg, P. (1999). The Hybrid Ventilation Process - Theoretical and Experimental Work. Air Infiltration Review 21(1): pp. 1-4.

Heiselberg, P. (2000). Design Principles for Natural and Hybrid Ventilation. Healthy Buildings 2000, 2: 35-46.

Hunt, G.R., P. Cooper, and P.F. Linden (2000). Thermal Stratification Produced by Plumes and Jets in Enclosed Spaces. in RoomVent 2000: Ventilation for Health and Sustainable Environment. 2000. University of Reading: Elsevier.

Hunt, G.R., P. Cooper, and P.F. Linden (2001). Thermal Stratification Produced by Plumes and Jets in Enclosed Spaces. Building and Environment, 36: 871-882.

Irving, S. and E. Uys. (1997). Natural Ventilation in Non-domestic Buildings. Applications Manual AM10: 1997. Chartered Institution of Building Services Engineers, London.

Kavanaugh, S. (2000). Fan Demand and Energy. ASHRAE Journal, June 2000: 47-55.

Knoll, B. (1992). Advanced ventilation systems - state of the art and trends. Coventry, AIVC.

Knoll, B. and W. Kornaat (1991). Controlled Natural Ventilation. 12th AIVC Conference - Air Movement & Ventilation Control Within Buildings, Ottawa, Canada.

Knoll, B. and J. C. Phaff (1998). Controlled Natural Ventilation for Commercial and Industrial Buildings. 19th AIVC Conference - Ventilation Technologies in Urban Areas, Oslo.

Komor, P. (1997). Space Cooling Demands from Plug Loads: Less Than One Watt per Square Foot. ASHRAE Journal, December: 41-44.

Leal, V., et al. (2000). *Energy Impact of Ventilation Rates*. in *RoomVent 2000 - 7th International Conference on Air Distribution in Rooms*. University of Reading, UK: Elsevier.

Levermore, G. J., A. M. Jones, et al. (2000). Simulation of a Naturally Ventilated Building at Different Locations. ASHRAE Transactions, 106(2): 402-407.

Linden, P.F. (1999). *The Fluid Mechanics of Natural Ventilation.* Annual Review of Fluid Mechanics, 31: 201-238.

Leyten, J. L. and S. R. Kurvers (2000). Robustness of Buildings and HVAC Systems as a Hypothetical Construct Explaining Differences in Building Complaint Rates. Healthy Buildings 2000, 2: 469-474.

Li, Y., et al. (1999). Analysis Methods for Natural and Hybrid Ventilation - An IEA ECB Annex 35 Literature Review. Proceeding of the 3rd International Symposium on Heating, Ventilation and Air Conditioning. Shenzhen, China.

Limb, M. J. (2000). Duct Cleaning: An Anotated Bibliography. Coventry, England, AIVC.

Lorenzetti, D.M., (DRAFT) (1999a). A Direct Error Measure for Affine Models of Nonlinear Algebraic Equations. Society for Industrial and Applied Mathematics (SIAM). J. Sci. Comput.

Lorenzetti, D.M., (DRAFT) (1999b). Regulating Newton-Raphson's Method by Unconstrained Minimization of a Weighted Sum of Squared Residuals. Society for Industrial and Applied Mathematics (SIAM). J. Sci. Comput.

Lorenzetti, D.M., (DRAFT) (1999c) Accelerating the Newton-Raphson's Method Solution of Multizone Airflow Systems.

Lorenzetti, D.M., (DRAFT) (2000). Computational Aspects of Nodal Multizone Airflow Systems.

Marion W and K Urban (1995). User’s Manual for TMY2s National Renewable Energy Laboratory.

Martin, A.J. (1995) Control of Natural Ventilation. BSRIA Technical Note TN 11/95; The Building Services Research and Information Association.

Martinez, D., D. Fiala, et al. (2000). Predicted Comfort Envelopes for Office Buildings with Passive Downdraught Evaporative Cooling. RoomVent 2000: Ventilation for Health and Sustainable Environment, University of Reading, Elsevier.

Mendell, M. J., W. J. Fisk, et al. (1996). Elevated Sympton Prevalence Associated with Ventilation Type in Office Buildings. Epidemiology, 7 (6): 583-589.

NADCA (1992). Mechanical Cleaning of Non-porous Air Conveyance System Components. Washington, DC, National Air Duct Cleaners Association.

NAIMA (1993). Cleaning Fibrous Glass Insulated Air Duct Systems. Alexandria, VA, North American Insulation Contraactors Association.

Nicol, F. and I. Raja (1997). Modeling Temperature and Human Behavior in Buildings. IBPSA News, 9 (1): 8-11.

Olesen, B. W. (2000). Guidelines for Comfort. ASHRAE Journal, August: 41-46.

Orme, M. (1999). AIVC Technical Note 51 – Applicable Models for Air Infiltration and Ventilation Calculations. Coventry, AIVC.

Orme, M.S. (2000). Advances in Natural Ventilation Design Procedures. RoomVent 2000: Ventilation for Health and Sustainable Environment. University of Reading: Elsevier.

Oseland, N. A. (1998). Acceptable Temperature Ranges in Naturally Ventilated and Air Conditioned Offices. ASHRAE Transactions, 104 (1): 1018-1030.

Petherbridge, P., N.O. Millbank, and J. Harrington-Lynn. (1998). Environmental Design Manual: Summer Conditions in Naturally-Ventilated Offices. Building Research Establishment (BRE): Garston, Watford, UK.

Säateri, J. (1998). A Proposal for the Classification of the Cleaniness of New Ventilation Systems. 19th AIVC Conference - Ventilation Technologies in Urban Areas, Oslo, AIVC.

Wilkins, C. and M. H. Hosni (2000). Heat Gain from Office Equipment. ASHRAE Journal, June 2000: 33-44.

Woloszyn (2000). *Combined Moisture, Air and Heat Transport Modeling Methods for Integration in Building Simulation Codes*. RoomVent 2000 – 7th International Conference on Air Distribution in Rooms, University of Reading, UK.

Appendix A: CEC RFP Issues

The California Energy Commission (CEC) Public Interest Energy Research (PIER) Request for Proposals for the Buildings Energy Efficiency Program Area identified four key issues of concern. These four issues identify energy problems facing buildings in California and present opportunities to have a significant positive impact. This appendix discusses the relationship of the application of natural ventilation systems to the four key issues based on information in this report.

Issue #1 Energy consumption is rapidly increasing in hotter, inland areas as new building construction increases in these areas.

A key intent of natural ventilation systems is the reduction of energy consumed to cool and ventilate buildings. As discussed in this report, natural ventilation is not a technology ideally suited to the hotter, inland areas of California as ambient air cooler than the indoor cooling setpoint and of sufficient dryness is required to adequately cool a building. However, natural ventilation could be used in these areas either as a night cooling system or as in conjunction with a mechanical cooling system as a hybrid strategy.

Issue #2 Development of energy efficient products and services needs to adequately consider non-energy benefits, such as comfort, productivity, durability, and decreased maintenance.

Since natural ventilation systems directly affect building ventilation systems and rates, the potential exists to have a significant impact on occupant comfort and productivity. That impact could be either positive or negative depending on the natural ventilation system design, installation, operation and maintenance. Some published studies have reported improved occupant health and comfort in naturally ventilated commercial buildings. While it is not possible to estimate potential impacts on productivity for any given building, Fisk and Rosenfeld (1997) have estimated that nationwide impacts of better indoor environments are in the billions of dollars.

Since natural ventilation systems rely on natural driving forces instead of mechanical fans and air-conditioning to control comfort and IAQ in buildings, they may not reliably control comfort and IAQ under all ambient conditions. Proper design, maintenance, and operation of is critical to attaining acceptable performance from natural ventilation systems.

Issue #3 Building design, construction, and operation of energy-related features can affect public health and safety.

The above discussion addressing Issue #2 also applies to public health. Natural ventilation systems could have either a negative or positive impact on public health, and therefore care needs to be taken in their application. In addition, natural ventilation could have a negative impact on the moisture load in non-residential buildings in humid climates. Since most of the moisture load for many non-residential buildings is brought into a building through ventilation, increasing ventilation and eliminating or reducing air-conditioning can increase this moisture load.

Issue #4 Investments in energy efficiency can affect building and housing affordability and value, and the state's economy.

As discussed in response to Issue #1, natural ventilation systems can reduce building cooling and fan energy use and, therefore, reduce operating costs to improve building affordability and value. However, these potential savings will vary widely depending on building type, climate and other factors. No significant impacts are expected on the energy-related costs of construction.

LoopDA – Natural Ventilation Design and Analysis Software

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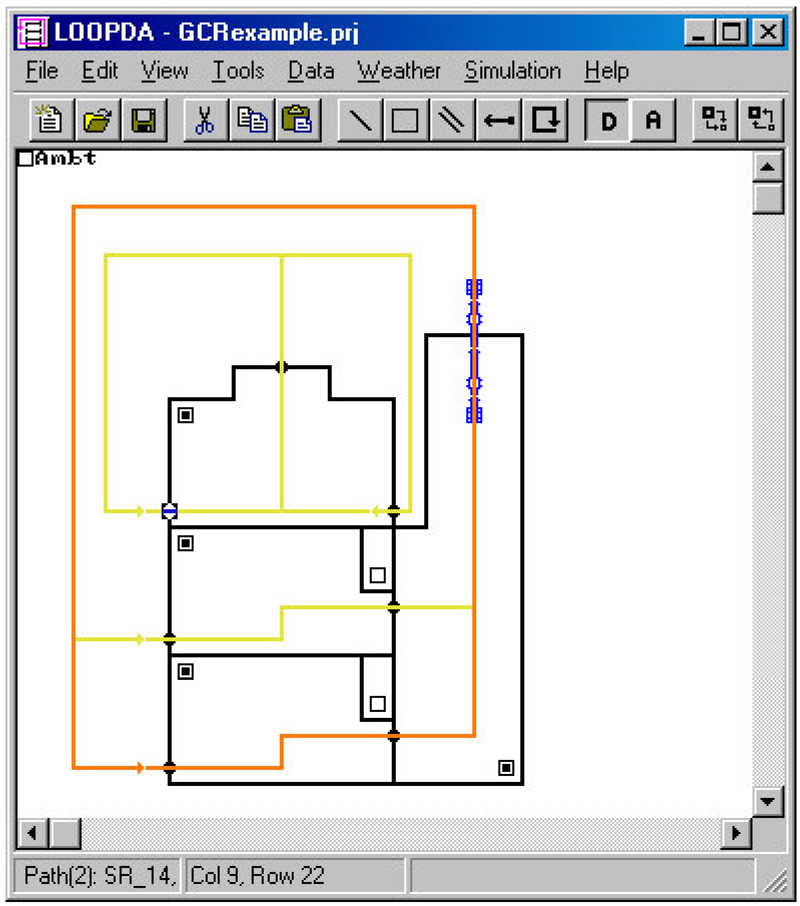

National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

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ABSTRACT

The *Loop Equation Design Method* has been proposed for sizing ventilation airflow components of natural and hybrid ventilation systems. While the approach has been demonstrated on a limited basis, the method has been automated in order to better evaluate its reliability under a more controlled, i.e., less error-prone, environment. This report describes a computer program developed by NIST that implements the *Loop Equation Design Method* of sizing the openings of naturally ventilated buildings. The tool, referred to as *LoopDA* for Loop Design and Analysis, is integrated with an existing multi-zone analysis tool CONTAMW. LoopDA provides the designer of natural ventilation systems with an environment in which to perform and document the process of designing the opening sizes of natural ventilation systems and analyzing the system behavior under a variety of operating conditions. This report describes the first version of the LoopDA program, provides an example of its application to the design of a naturally ventilated building and describes needs for future enhancements to the tool to increase its usefulness within the design community.

Key Words: airflow analysis; building technology; computer program; design tool; indoor air quality; multizone analysis; natural ventilation

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Table of Contents

1 INTRODUCTION

NIST is investigating the application of state-of-the-art natural ventilation concepts in small commercial buildings in California and developing design methods for natural ventilation in new and retrofit applications. An earlier report [1] reviewed the application of natural ventilation in commercial buildings including the associated technology, potential advantages of natural ventilation and issues that need to be addressed. The report also addressed opportunities and issues specific to the application of natural ventilation to commercial buildings in California including analysis of climate suitability via a new ventilative cooling metric, consideration of ambient air quality, and discussion of relevant codes and standards. It also reviewed current design and analysis processes and tools and described a plan for the development of new design and analysis guidance and tools.

The key recommendation of the earlier report was to develop a software tool to implement the *Loop Equation Design Method* within the existing multi-zone modeling environment of CONTAM [2] to gain the advantages of the existing user interface, airflow element base, and capability to perform detailed analysis after completing the natural ventilation system design. The *Loop Equation Design Method* (presented in detail by Emmerich et al. [1]) is a method for sizing of natural ventilation components that is general and practical and allows direct consideration of stack and wind-driven airflow that is critical in addressing natural ventilation airflow. The tool should assist the designer in performing the needed steps of developing the natural ventilation system design including: establishing the global geometry and topology of zones and interconnecting flow paths, establishing design conditions, setting up and solving the representative loop equations based on the "design" form of the airflow components, and analyzing operation under a variety of conditions.

This report describes the first version of the LoopDA program (for **Loop D**esign and **A**nalysis tool), which was developed as a version of CONTAM. The report is organized into three main sections – Loop Equation Design Method (a brief review of the method implemented in LoopDA), the LoopDA Software Tool (a description of the program and how to use it), and Design Example Using LoopDA (an example application of LoopDA to the design of a natural ventilation system for a small commercial building).

2 LOOP EQUATION DESIGN METHOD

The Loop Equation Design Method that is proposed for the Design Development stage of the overall design process of a natural ventilation system is described in detail by Emmerich, Dols, and Axley[1]. (Note: The other design stages – Conceptual Design and Design Performance Evaluation – both precede and follow the Design Development Stage and are also described in [1]. Detailed theory of the method is presented in [3] and [4].). The *Loop Equation Design Method* consists of the following eight steps:

1. Lay out the global geometry and multi-zone topology of the natural ventilation flow loops for each zone of the building.
2. Identify an ambient pressure node and additional pressure nodes at entries and exits of each flow component along the loops.
3. Establish design conditions: wind pressure coefficients for envelope flow components, ambient temperature, wind speed and direction, and interior temperatures; evaluate ambient and interior air densities.
4. Establish first-order design criteria (i.e., a ventilation objective) and apply continuity to determine the objective design airflow rates required for each natural ventilation flow component.
5. Form the forward loop equations for each loop established in step 1 above by systematically accounting for all pressure changes while traversing the loop.
6. Determine the minimum feasible sizes for each of the flow components by evaluating asymptotic limits of the loop equation for the design conditions.
7. Develop and apply a sufficient number of technical or non-technical design rules or constraints to transform the under-determined design problem defined by each loop equation into a determined problem.
8. Develop an appropriate operational strategy to accommodate the regulation of the natural ventilation system for variations in design conditions.

As detailed in the following section, the user will perform some of these steps explicitly (e.g., Step1). Other steps are performed implicitly by LoopDA without user interaction (e.g., Step 5). Still others are accomplished by a combination of explicit and implicit actions (e.g., Step 3).

3 THE LOOPDA SOFTWARE TOOL

LoopDA was developed as a means to perform the eight steps of the *Loop Equation Design Method* presented in the previous section. While it does not fully automate all eight steps, it greatly simplifies and provides a means to manage the entire process.

Specifically, the software accommodates each of the steps as follows:

1. LoopDA provides a SketchPad interface that enables you to draw a schematic representation of the global geometry and multizone topology of the building and to draw the natural ventilation flow loops through the relevant airflow paths of the building.
2. The SketchPad provides the ambient pressure node and keeps track of the pressure nodes associated with each of the airflow paths that you identify on the SkethPad. The direction in which you draw the loops establishes the intended direction of natural ventilation airflow for the purposes of design.
3. LoopDA provides for the establishment of design conditions by allowing you full control in setting ambient conditions of temperature, wind speed and direction. It also enables you to set the design temperatures of all airflow paths and automatically calculates the air densities of each. The program also provides a means to input the wind pressure coefficient of all exterior openings.
4. LoopDA provides a means for you to define the first-order design criteria for each airflow path to be sized, however, it is up to you to select the design criteria and to ensure that continuity is not violated in the event that an opening serves multiple flow loops.
5. Once you have established the geometry, design conditions and criteria and drawn the flow/pressure loops, LoopDA will form the forward loop equations for each loop by traversing the loop in the established direction and accounting for pressure changes due to the pressure/flow relationships of the various flow components, wind and stack effects.
6. LoopDA calculates the minimum feasible sizes of each unsized flow component in a loop by evaluating asymptotic limits of the loop equation for the design conditions.
7. LoopDA provides the ability to export loop information to a spreadsheet template (provided with the program) that displays all the data associated with a given loop, generates asymptotic plots and thus provides a means to view relationships between the flow components of a loop. This aids the application of design constraints, selection of component sizes and documentation of the steps in designing the natural ventilation airflow paths.
8. Having sized the natural ventilation airflow, you can then utilize LoopDA to analyze the building performance under varying conditions. LoopDA implements the established multizone building simulation capabilities of CONTAMW 2.0. You perform analysis to investigate the effects of unintentional air infiltration, non-design weather conditions, and forced-flow elements to simulate hybrid ventilation systems.

3.1 Installing and Running LoopDA

LoopDA runs on Windows 95/98/NT/XP/2000. There are three basic components to LoopDA software system: the main Windows executable program *LoopDA.EXE*, the spreadsheet template *LOOPDATEMPLATE.XLS*, and the analysis or simulation engine *CONTAMX2L.EXE*.

The setup files are contained in the self-extracting archive file "LoopDAz.exe." Simply execute the self-extracter to decompress the setup files. Extract the files to the subdirectory of your choice, or simply select the default location. Once you have extracted the setup files, you can run the setup program, "setup.exe." This will prompt you to perform an automatic installation of the program. Read the instructions to complete the installation.

- **Files Installed**

The following table lists the files installed by the setup program. For each file, the directory to which it is installed, the name and a brief description are given. The <program> directory is that selected by you when you install the program. The default is C:\Program Files\LoopDA. The <font> directory is that of the operating system fonts. The default is <windows>/FONTS, where <windows> depends on the operating system you are using, e.g., Windows 2000 <windows> = WINNT and Windows 95/98 <windows> = WINDOWS.

Directory	File Name	Description
<program>	LoopDA.exe	User interface
	Contamx2l.exe	Solver
	cwhelp2.hlp cwhelp2.cnt	CONTAMW help files
	olch2d32.dll roboex32.dll	Charting and help display dynamic link libraries
	LoopDA.doc	LoopDA documentation to be used in conjunction with CONTAMW help files
<program>\samples	*.prj	Sample project files
	*.xls	Spreadsheet files
<font>	walton##.fnt	SketchPad fonts where ## ranges from 01 to 16 for different SketchPad resolutions

- **Uninstalling LoopDA**

The LoopDA setup program will also provide you with an uninstall feature. You uninstall LoopDA much as you would a typical Windows program. Access the **Control Panel** from the **Settings** selection of the **Start** menu. Select Add/Remove Programs from the Control Panel. Select LoopDA from the list of installed programs and click the "**Add/Remove…**" button to uninstall LoopDA.

- **Running LoopDA**

After you install LoopDA, you can run it by selecting LoopDA from the NIST program group of the Start menu.

3.2 Basic Approach to Design Using LoopDA

This section present a brief over of the basic steps to take to implement the Loop Equation Design Method using LoopDA to size the airflow components of a natural ventilation system. Ideally you would perform steps a – d once for a given model of a building and iterate through steps e and f. The details of each of these steps are presented in the following section *Working with LoopDA*. Step g is the process of performing simulations based on your design.

a. Define ambient design conditions (see Working with Weather and Wind)
   Set temperature, wind speed and wind direction

b. Draw the elevation view of the building (see Working with Walls and Zones)
   Draw the walls
   Define the zones

c. Draw ventilation airflow and duct flow paths to be sized (see Drawing Airflow Paths and Drawing Ducts)

d. Define airflow and duct flow elements (see Working with Inverse Airflow Elements and Working with Inverse Duct Flow Elements)
   Select inverse element type
   Set design airflow rate Q_{des}
   Set design temperature T_{des}
   Set wind pressure coefficient $C_p(\theta)$

e. Draw loops (see Working with Pressure Loops)
   View loop data
   Export loop data

f. Import into spreadsheet (see Working with the LoopDA Spreadsheet)

g. Perform analysis
   Set the forward element properties based on design values.
   Switch to *analysis mode* and run simulation as with CONTAMW.

3.3 Working with LoopDA

This section serves as a user guide for LoopDA. Using LoopDA is very similar to using CONTAMW, so the information contained in this section is presented as a supplement to the CONTAMW 2.0 User Manual [2] that is available while running LoopDA as an online help system. References to sections of the CONTAMW User Manual / online help will be given in the following sections as {CW: Section} and the areas in which the two programs differ will be presented in detail.

3.3.1 Working with the SketchPad

When working with LoopDA, a major portion of your interaction will be with the SketchPad or drawing region of the interface to develop a schematic representation of your building. The basic use of the SketchPad is very similar to CONTAM, i.e., drawing, selecting and editing building component data. {CW: Working with the SketchPad} The fundamental difference is that LoopDA presents an elevation view of a vertical section of a building, whereas CONTAMW presents plan views of individual levels of a building. In CONTAMW there are level commands and toolbar buttons that provide access to different building levels. These commands are not available in LoopDA.

Because LoopDA is meant to be both a "true" design tool as well as an analysis tool, it has an additional mode of operation that is not in CONTAMW, i.e., the *Design mode*. You size ventilation components in the design mode and therefore an analysis would not be appropriate due to undefined components. The analysis mode is intended to enable the evaluation of a given design once all of the components have been defined or sized. While in the analysis mode, the drawing tools will be deactivated so that you can't modify your design. You set the mode of operation via the analysis and design toolbar buttons shown below in Figure 1.

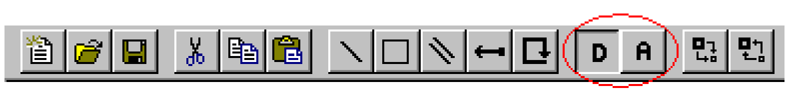


Figure 1 – LoopDA toolbar highlighting Design/Analyses mode buttons

3.3.2 Working with Weather and Wind

The weather and wind features are used to establish the design ambient conditions for both design and analysis modes of operation. However, only the Steady State weather data is relevant to the design mode of operation. Set the ambient temperature, wind speed and direction of the Steady State weather data of the Weather and Wind Properties prior to working with your airflow loops as this data is used in forming the pressure loop equations. Note that because LoopDA presents an elevation view, the wind direction should be from either the left or right side of your drawing. This corresponds to either a direction of 0º or 180º respectively, based on the default *relative north* value of -90º (CONTAMW defaults to 0º) as also established in the Weather and Wind Properties. Also, set the reference wind speed data to obtain the desired *wind speed modifier* for your building location {CW: Defining Steady State Weather and Wind}

The CONTAMW User Manual contains a detailed presentation of how weather and wind are handled by CONTAMW and LoopDA in the analysis mode. {CW: Working with Weather and Wind} As presented in that section, both steady state and transient weather data can be implemented depending on the type of simulation you are performing.

3.3.3 Working with Walls and Zones

The mechanics of drawing walls to form zones are exactly the same as in CONTAMW. The main difference between LoopDA and CONTAMW is that you are drawing elevation views of a building as opposed to plan views. Each drawing that you create should represent a vertical section of the building in question. To represent multiple sections, you could either draw them individually on a single SketchPad, or you can create individual LoopDA project files for each building section. {CW: Drawing Walls, Ducts and Controls; CW: Working with Walls}

Walls must be drawn so that fully bounded regions are created that make up the *zones* of your building representation. The properties of each zone must then be defined by a zone icon as typical for building components. {CW: Working with Zones} The zone properties are not needed in the design process, but are required during the analysis phase.

3.3.4 Working with Airflow Paths

In LoopDA, airflow paths are the openings between zones, including the ambient, that form direct connections between the zones (as opposed to ducted connections discussed below). In the design mode, you first lay out (draw) the location of the natural ventilation airflow paths that will make up the ventilation flow loops and then define their design properties.

3.3.4.1 Drawing Airflow Paths

You draw airflow paths in LoopDA exactly as done in CONTAMW. However, in LoopDA, you can only place airflow paths directly on walls. {CW: Creating Airflow Paths}

3.3.4.2 Defining Airflow Paths

Once a flow path is drawn you must define its design properties in order to use the path in a ventilation airflow loop. The following items are relevant to the *design mode* of operation, i.e., to form *Loop Design Equations*.

Airflow Element – *Airflow elements* describe the mathematical relationship between the flow through an airflow path and the pressure drop across the path. You must select an airflow element type prior to setting the other parameters. As presented in the following subsection, the design mode is only concerned with *Inverse Airflow Element* types. LoopDA currently supports only two types of inverse airflow elements, but all types of CONTAMW airflow elements are supported in the *analysis mode*. You should create an airflow element for each flow path you want to design in order to maintain a unique set of parameters for each path.

Elevation – Set the elevation of each airflow path relative to the reference height of zero for the bottom of the building. This value will be used in calculating stack pressures in both the design and analysis modes.

Wind Pressure – Set the wind pressure to be variable and define a wind pressure coefficient profile. You can simply set this to be a constant profile or to vary according to the angle of incidence of the wind on the wall or flow path. {CW: Airflow Path – Wind Properties} Care should be taken when defining flow paths on horizontal walls, as they will default to have azimuth angles that might not make sense. Be sure to set the reference wind speed modifier to the desire value either individually for each flow path or globally via the Weather data that defaults to provide a modifier of 1.0.

Detailed information on the analysis parameters are provided in {CW: Working with Airflow Paths}, and details of working with the Inverse Airflow Element data are provided below.

3.3.5 Working with Inverse Airflow Elements

Basically, an *inverse airflow element* is one that can be sized using the loop equation design method. In CONTAM, airflow component equations are formulated in the so-called "forward" form while the loop method uses these same equations in "inverse form" – a form relating the pressure drop across components to the volumetric (or mass) flow rate and characteristic design parameters (CDP), e.g., an area for an orifice element. A detailed discussion of inverse airflow elements is presented in Axley [3] and [4].

This version of LoopDA supports two types of inverse airflow elements: orifice and general power law. The mathematical relationships for each are presented here in forward and inverse form.

- **Orifice Element**

Forward form: $$\dot{V} = C_d A_{orfc} \sqrt{2\Delta p / \rho}$$

Inverse form: $$\Delta p = \frac{\rho \dot{V}^2}{2 C_d^2 A_{orfc}^2}$$

Characteristic Design Parameter: A_{orfc}

Corresponding Analysis Parameter: *Cross sectional area*

- **General Power Law Element**

Note: This element can be used to represent a range of flow paths, including a self-regulating vent when a relatively large value of the exponent *n* is specified [2].

Forward form: $$\dot{V} = C\left(\Delta p\right)^n$$

Inverse form: $$\Delta p = \left(\frac{\dot{V}}{C}\right)^{\frac{1}{n}}$$

Characteristic Design Parameter: C

Corresponding Analysis Parameter: *Flow coefficient (C)*

3.3.5.1 Creating Inverse Airflow Elements

To create an inverse airflow element you select the "New Element" button on the Flow Element page of the Airflow Paths Property Sheet that is displayed when defining an airflow path. This will display a list of all available types of *forward airflow elements*. Select either the general *power law element*, represented in the list as *Q = C(dP)^n*, or the *orifice element* from the list of elements on the Airflow Element Models dialog box. This will reveal the Airflow Element Properties sheet that contains two pages of parameters: one that contains the analysis parameters specific to the type of model selected and one containing the design parameters for the inverse element.

3.3.5.2 Defining Inverse Airflow Elements

Figure 2 shows the Airflow Element Properties sheet for an orifice element and the design parameters associated with the element. The parameters on the Design page are those used in formulating the pressure loop equations along with the previously mentioned airflow path properties.

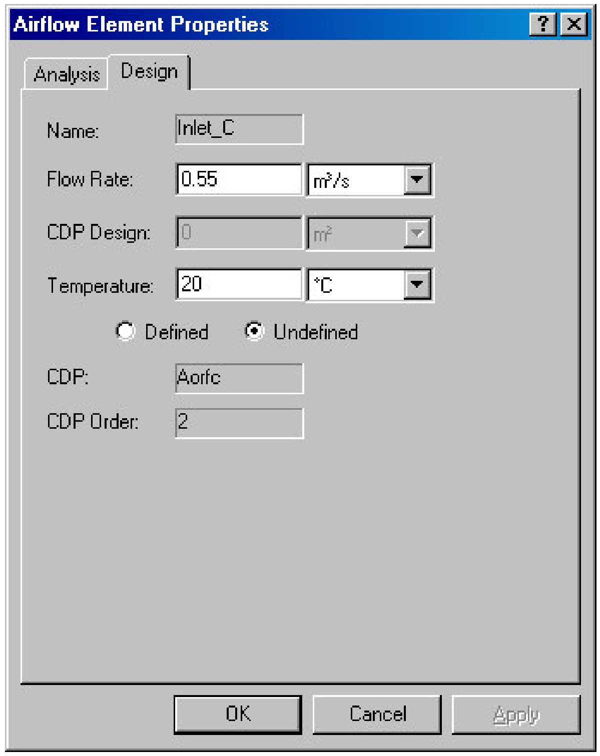


Figure 2 – Airflow Element Properties sheet displaying design data for an inverse orifice element

For each of these inverse elements the design page displays information that is specific to the element for which the properties are being displayed. The following is a description of each of the properties displayed.

- **Name:** This is the airflow element name you provide for this element. This name is used for both the forward and inverse flow element.
- **Flow Rate:** Specify the design flow rate for this element. It is your responsibility to ensure that design flows do not violate continuity when multiple loops pass through common flow paths, as is the case for Loops 2 and 3 in Figure 9 of the example presented later.
- **CDP Design:** Once you have selected a value for the *CDP* (characteristic design parameter), enter it here and select *Defined* as described below. The type of parameter this value represents will depend on the type of inverse element you are sizing.
- **Temperature:** Set the design air temperature for this element.
- **Defined/Undefined:** Select *Undefined* when the element has not yet been sized. As you select sizes for elements, you set their *CDP Design* values and set them to be *Defined*.
- **CDP:** This is the name given by LoopDA for this particular element. This will be either A_{orfc} or C_e corresponding to the *orifice* and *power law* elements respectively. When you view and export loop data, a distinct area or diameter identifier will be provided for the element. This identifier will include the path number assigned by LoopDA.
- **CDP Order:** This is the order of the exponent of the design parameter as it would appear in the loop design equation as detailed by Axley [3] and [4]. This will be either 2.0 or 1/n corresponding to an area (orifice) or flow exponent (general power law) respectively.

3.3.6 Working with Ducts

You can use LoopDA to size duct segments and inlet and outlet terminals that represent stacks or connections between zones. In the design mode, you first draw the individual duct segments then define their design properties. LoopDA implements the *Darcy-Colebrook* duct flow element. This element provides for the sizing of both *duct flow segments* based on a friction factor and *fittings* (inlets and outlets) based on a loss coefficient.

3.3.6.1 Drawing Ducts

You draw ducts in LoopDA exactly as done in CONTAMW. However, in LoopDA, you are working in the elevation view. {CW: Working with Ducts} You should draw duct segments for each inlet, airflow segment and outlet of a duct as shown in the figure below. This will provide a separate term in the loop equation for each component of the duct system. The details of defining duct segments and terminals will be presented in the following sections.

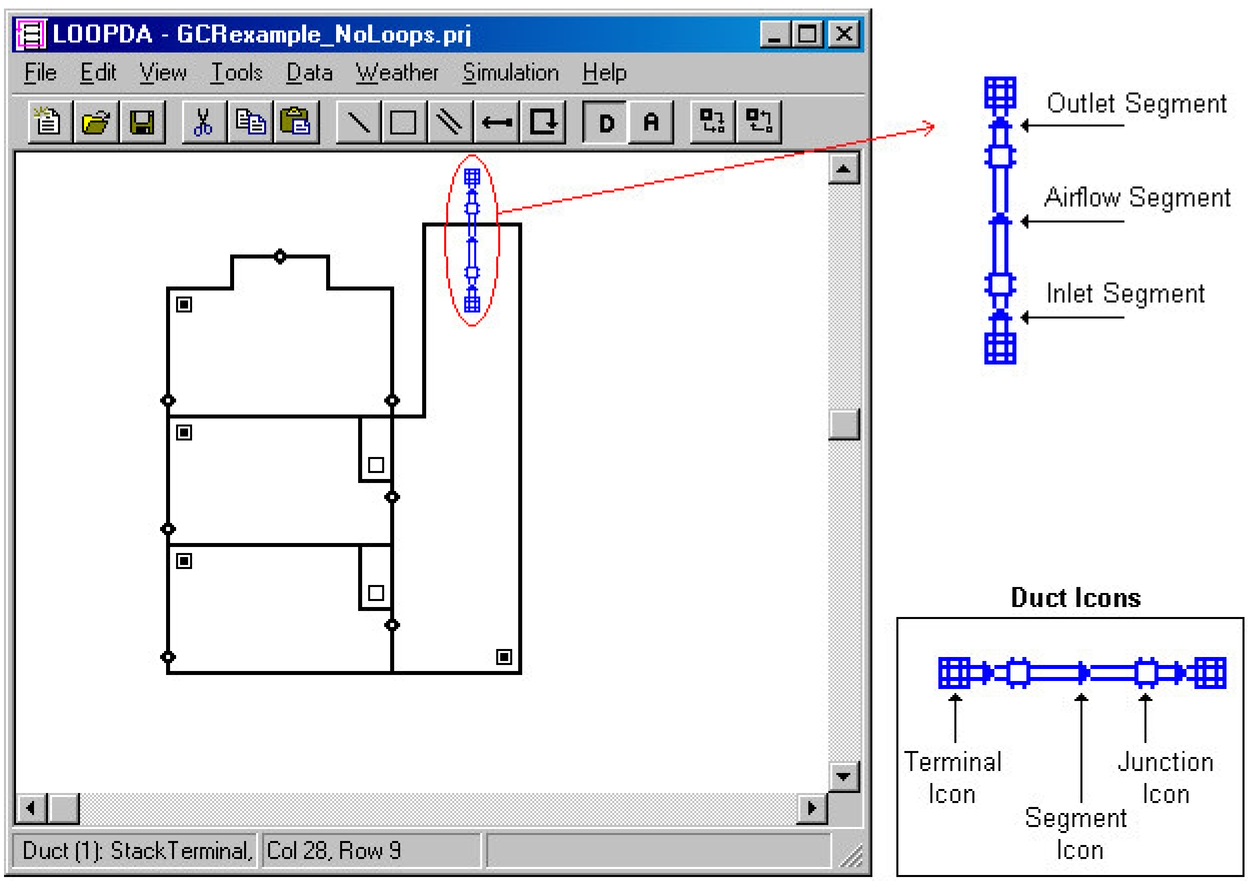


Figure 3 – Detail for drawing ducts for loop analysis

3.3.6.2 Defining Ducts

Once a duct is drawn you must define its design properties in order to use it in a ventilation airflow loop. The following items are relevant to the *design mode* of operation, i.e., to form *Loop Design Equations*.

Duct Flow Element – *Duct flow elements* describe the mathematical relationship between the flow through a duct segment and the pressure drop across the path. You must select a duct flow element type prior to setting the other parameters. As presented in the following subsection, the design mode is only concerned with *Inverse Duct Flow Element* types. LoopDA currently supports only one type of inverse duct flow element, but all types of CONTAMW duct flow elements are supported in the *analysis mode*.

Select whether you want to create an *Airflow Segment* or *Terminal/Fitting* (use this for creating *inlets* and *outlets* that you want to size based on a loss coefficient). This will enable/disable and zero-out various input parameters for the duct to help insure that you define only those that are relevant to the type of segment as described below.

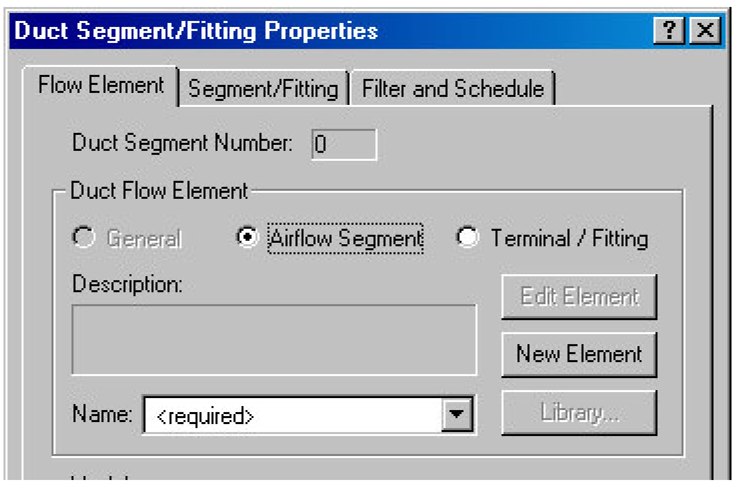


Figure 4 – Duct segment/fittings properties sheet

Segment Length – If you are defining a segment icon to be a duct segment (as opposed to a terminal), provide a value for the *Duct segment length* and make sure the *Sum of loss coefficients* is set to zero.

Friction Factor – If you are defining a segment icon to be an *airflow segment*, provide a value for the *Friction factor*. You can use the friction factor calculator provided on the Duct Airflow Element Properties input dialog box to help determine this value and the *Roughness* value for analysis.

Segment Sum of Loss Coefficients – If you are defining a segment icon to be a duct *Terminal*/Fitting (inlet or outlet), then provide a value for the *Sum of loss coefficients* and make sure the *Duct segment length* is set to zero.

Elevation – Set the *elevation* of each *duct junction* and *terminal icon* relative to the reference height of zero for the bottom of the building. This value will be used in calculating stack pressures in both the design and analysis modes. Note that the difference in elevations of adjacent junctions is not necessarily the same as the length of the segment between them.

Wind Pressure – See previous Defining Airflow Paths section.

3.3.6.3 Working with Inverse Duct Flow Elements

Inverse duct flow elements are similar in nature to airflow elements. This version of LoopDA supports only the Darcy-Colebrook type of inverse duct flow element. However, this element can be used to size either a *Duct component* (*Airflow segment*) or *Duct fitting component* (*Fitting/Terminal*) as described by Axley [2]. The forward form shown below is that implemented in CONTAM. This form can be split into two terms: one containing the loss due to the friction factor *f* (and the duct dimensions) and one containing the losses due to fittings ΣC_d.

- **Darcy-Colebrook Element**

Forward form:

$$\dot{V} = \sqrt{\frac{2A^2 \Delta p}{\rho \left(fL / D_h + \Sigma C_l \right)}}$$

Inverse forms:

Duct component

$$\Delta p = \frac{\rho \dot{V}^2}{2A^2} \frac{fL}{D_h} = \frac{\rho \dot{V}^2 fL}{2D_e^5}$$

Characteristic Design Parameter: Equivalent duct diameter D_e which simplifies to the actual diameter *D* for circular ducts (See Chapter 34 of [5] for a discussion of hydraulic, actual and equivalent duct diameters.)

Corresponding Analysis Parameter: *Duct shape and dimensions*

Relevant Parameters: Set segment *Sum of loss coefficients* C_l to 0.0. Design value for friction factor *f* and *Duct Shape*.

Duct fitting component

$$\Delta p = \frac{\rho \dot{V}^2}{2A^2} \Sigma C_l$$

Characteristic Design Parameter: Opening area *A*

Corresponding Analysis Parameter: *Duct shape and dimensions*

Relevant Analysis Parameter: Set *Duct segment length L* to 0.0
Note: *friction factor* and *duct shape and dimensions* are not relevant to fittings

3.3.6.4 Creating Inverse Duct Flow Elements

To create an inverse duct flow element you select the “New Element” button on the Flow Element page of the Duct Segment/Fittings Properties sheet that is displayed when defining a duct flow path. This will reveal the Duct Airflow Element Properties sheet that contains three pages of parameters: one that contains the analysis parameters specific to the Darcy-Colebrook duct model, one containing *Shape, Size and Leakage* data and one containing the *Design* parameters for the inverse element.

3.3.6.5 Defining Inverse Duct Flow Elements

Figure 5 shows the Duct Airflow Element Properties sheet for a Darcy-Colebrook element and the design parameters associated with the element. The parameters on the *Design* page are those used in formulating the pressure loop equations along with the previously mentioned duct flow path properties.

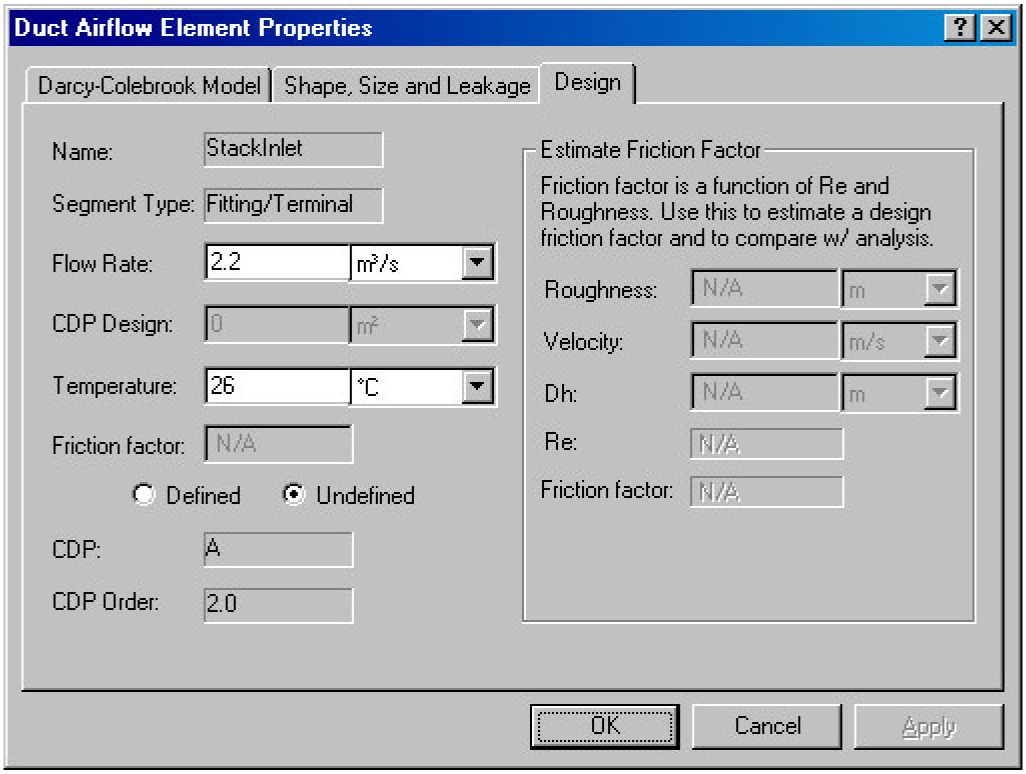


Figure 5 – Duct Airflow Element Properties sheet displaying design data for a Darcy-Colebrook element (Fitting/Terminal)

For each of these inverse elements the design page displays information that is specific to the element for which the properties are being displayed. The following is a description of each of the properties displayed.

The Name, Flow Rate, Temperature and Defined/Undefined items are the same as described in the case of inverse airflow elements.

- **Segment Type:** This indicated whether the duct segment icon represents an Airflow segment or a Fitting/Terminal segment as selected when defining the Duct Segment/Fitting Properties (see Figure 4).
- **CDP Design:** Once you have selected a value for the *CDP* (characteristic design parameter), enter it here and set the element to be "defined." The type of parameter this value represents will depend on the type of inverse element you are sizing. This will be either an *equivalent duct diameter* D_e or opening area A depending on whether you are sizing a duct or terminal, respectively. Further, D_e is the actual diameter when dealing with circular ducts as described in Chapter 34 of the ASHRAE Fundamentals [5].
- **Friction Factor:** This value is only required for *airflow segments* and is ignored for *fittings/terminals*. It is dependant on the roughness and Reynolds number. Therefore, it is

indeterminable at design time, because the flow, and hence the velocity, in the duct is not known. You can use the right side of the page to estimate a design friction factor. Details on friction losses are presented in Chapter 34 of the ASHRAE Fundamentals [5].

- **CDP:** This is the name given by LoopDA for this particular element. This will display "A" or "De" to indicate either area or diameter for *fitting/terminal* segment or *airflow segment* respectively. However, when you view and export loop data, a distinct area or diameter identifier will be provided for the element. This identifier will include the duct segment number assigned by LoopDA.

- **CDP Order:** This is the order of the exponent of the design parameter as it would appear in the loop design equation as detailed by Axley [3] and [4]. This will be either 2.0 or 5.0 corresponding to an area (*fitting/terminal*) or diameter (*airflow segment*) respectively.

3.3.7 Working with Pressure Loops

Once you have defined the paths and ducts that you want to size, you can now form pressure loops that define the desired airflow paths of ventilation air through the building. The basic method consists of drawing loops by connecting design flow paths and ducts on the SketchPad in the direction that air should flow through them; selecting the loop to generate a loop equation; reviewing loop properties within LoopDA; exporting loop data to a spreadsheet template to view loop equation details, review asymptotic plots and apply design constraints to select component sizes. Once you decide on the size of an element in a loop, you return to LoopDA and set that element's CDP and regenerate the loop equation so that the defined element is "moved to the right hand side" of the loop equation. Continue this process until all elements in a loop are sized and for each loop under consideration.

3.3.7.1 Drawing Loops

Drawing loops is very similar to drawing walls with the wall drawing tool {CW: Drawing Walls}. Select the loop drawing tool from the toolbar as shown highlighted in Figure 6.

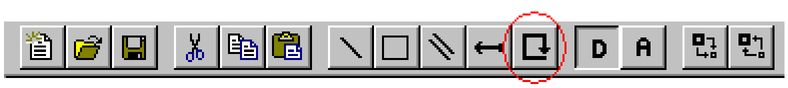


Figure 6 – LoopDA toolbar highlighting the Loop Drawing Tool button

The following rules apply when drawing loops:

- You must begin drawing loops in the ambient zone.
- Draw loops in the direction you want air to flow through the building.
- Each loop must end where it began (LoopDA will automatically complete the loop when you reach the beginning cell on the SketchPad).
- Each loop must contain exactly two flow paths that are connected to the ambient, i.e., an inlet into the building and an outlet from the building.
- Loops are allowed to cross over and share common sections with the exception of the loop direction/selection arrow.
- Loops may not cross over themselves.

3.3.7.2 Selecting Loops

To select a loop once it is drawn click on its direction arrow. This will highlight the loop in orange as shown later in the description of the pressure loops of the design example (see Figure 9).

3.3.7.3 Deleting Loops and Loop Elements

To delete a loop, select it to then click the Delete key on the keyboard or select Edit→Delete from the menu. You should always delete loops that pass through any airflow or duct flow paths before you move or delete the paths or ducts through which a loop passes.

3.3.7.4 Viewing and Exporting Loop Data

To access loop properties either select the loop then press the Enter key on the keyboard or double-click on the loop selection arrow. This will display the Pressure Loop Properties dialog box (see Figure 11 presented later in the Pressure Loops section of the design example). This dialog box displays the following information:

- **Loop Number:** This is an identification number assigned by LoopDA.
- **Name:** You can enter an optional name for this loop to help you identify it when you export it to a spreadsheet.
- **Description:** You can enter an optional detailed description for this loop to help you further identify it when you export it to a spreadsheet. This can be very useful as you progress through the iterative stage of sizing elements in that same loop.
- **Number of Loop Nodes:** This is the number of airflow paths, duct junctions, terminals and segments through which the loop passes.
- **Number of Equation Terms:** This is the number of terms that would appear on the left hand side of the pressure loop equation. There will be an equation term for each airflow path and duct segment through which the loop passes, i.e., the sizable components, whether defined or undefined.
- **Driving Pressures:** These are the pressure differences induced by the wind and buoyancy-driven airflows for the selected loop. In terms of the loop equation, these are the values that appear on the right-hand-side of the equation.

  Wind: This is the sum of the wind pressures acting on the two external openings of the loop in consideration.

$$\Delta P_w = \Delta C_p \frac{\rho_o C_h U_{met}^2}{2}$$

ΔC_p is the algebraic sum of pressure coefficients. It is summed positively when traversing the loop from the exterior to a wall surface and negatively otherwise.

ρ_o is the density of the outdoor air calculated by LoopDA based on the ambient temperature as entered in LoopDA (and CONTAMW) under Weather and Wind Parameters.

U_{met} is the design wind speed at the meteorological station as entered in LoopDA (and CONTAMW) under Weather and Wind Parameters.

C_h is the wind speed modifier determined based on terrain and elevation effects in LoopDA (and CONTAMW) under Weather and Wind Parameters.

Stack: This is the sum of the buoyancy-induced stack pressure differences determined by traversing the loop systematically in the order of airflow accounting for differences in density and elevation along the way.

$$\Delta P_s = g \sum \rho_{ij} \Delta z_{ij}$$

g	is the acceleration of gravity (9.81 m/s^2).
ρ_{ij}	is the density of air within the flow element based on the design air temperature of the inverse element.
Δz_{ij}	is the difference in elevation between two nodes in the loop. It is positive for drops and negative for rises in elevation along the loop.

Total Pressure Drop (RHS): This is the total pressure drop available to drive airflow through the undefined airflow components. This accounts for any defined Flow Element Terms within the loop in question and is the value that would appear on the right-hand-side (RHS) of the loop equation.

$$\Delta P_{Total} = \Delta P_s + \Delta P_w - \sum \Delta P_{defined}$$

- **Flow Element Terms:** This is a detailed accounting of each term that would appear on the left-hand-side of the loop equation. It includes the *Type* of component (path or duct), the component number # (as assigned by LoopDA), the *Name* of the characteristic design parameter including the appended component number, the *Order* of the exponent of the CDP as it would appear in the loop equation, the value of the element-specific *Numerator* that would be associated with this component in the loop equation, the *Asymptote* or minimum value of the CDP that would provide the total pressure drop equivalent to the RHS value above, whether or not the item is *Defined* or has been sized and should be accounted for on the RHS of the loop equation, and the *Value* of the CDP if it has been defined.

  The Element Term that is highlighted in this list will be that against which all others will be plotted when the asymptotic plots are generated by the spreadsheet once the loop data is imported into the LoopDA spreadsheet template. You can select the component against which you would like all others to be plotted. By default the CDP with the highest order is highlighted unless it is already defined. If all undefined elements have the same order, then the first element in the list is highlighted.

- **Export Loop Button:** Click this button to export loop data. You will be prompted to give the file a name (having a default extension of .txt). This will create a tab-delimited ASCII file that can be easily imported into the LoopDA spreadsheet template. Make note of the name and location of the file you save, so you can locate it for importing into a spreadsheet program.

3.3.8 Working with the LoopDA Spreadsheet

This version of LoopDA takes advantage of the powerful features of spreadsheet software by exporting loop data in a format compatible with typical spreadsheet programs. A spreadsheet template is provided with the software that simplifies the presentation of the loop equation data generated by LoopDA. Along with the LoopDA project file, the spreadsheet also serves as a means of documenting the steps you go through in performing your design analysis.

The sections immediately following provide the mechanics of using the LoopDA spreadsheet, whereas the practical use of the spreadsheet in the Pressure Loop Sizing Method is presented further along in the Design Example.

3.3.8.1 LoopDA Spreadsheet Template

The LoopDA spreadsheet template is a simple spreadsheet that contains headings for the loop data, a section that calculates plot ranges for the CDPs, and a chart for each set of loop data you import that automatically plots the imported data.

The exported data provide much more detailed information than is presented in the *Pressure Loop Properties* dialog box. The data is subdivided into the following sections:

- File Information
- Loop Information
- Outdoors
- Wind Pressures
- Stack Pressures
- Loop Flow Elements
- CDP Asymptotic Values
- Chart Data

3.3.8.2 Saving Loop Spreadsheets

Before you begin working with the LoopDA spreadsheet template, you should save it under a new name specific to your current project. It's up to you as to how you manage your loop spreadsheets. One way is to maintain a separate spreadsheet for each loop that contains the various stages of undefined elements. The template is preset with four sets of data pages and asymptotic plot pages. You can easily increase the number of pages by simply copying the existing ones.

3.3.8.3 Importing Loop Data

To import a LoopDA-generated loop file, open the file using your spreadsheet software and parse it as a tab-delimited file. Then simply select the top left cell of the desired sheet in the template (typically A1) and paste the data (values only using the Paste Special… command for example).

3.3.8.4 Plotting Loop Data

Data will be plotted automatically for up to five elements (four terms vs. one). You can expand this by simply copying the cells located in the bottom of column E to the column(s) on the right of E.

3.3.9 Performing Analysis

Be sure to set the forward element parameters based on your design values.

4 DESIGN EXAMPLE USING LOOPDA

4.1 Sample Building

The use of LoopDA to design a natural ventilation system is demonstrated using an example from Axley [3]. The sample building is based conceptually on the Inland Revenue Building in England (see [6] for more detail on this building). It is worthwhile to note that by using this sample building the Conceptual Building phase mentioned above is already completed – allowing us to focus on the Design Development phase.

Figure 7 shows an elevation section view of this building model. As seen in the figure, the building is three stories tall with the 1st and 2nd floors being ventilated by air flowing in through inlet *orifices a* and *c* and out through a common exhaust stack represented by *zone s* and *opening h*. The 3rd floor is ventilated by air flowing in through two *self-regulating inlet vents e* and *f* (see [3] for a detailed description of these vents) and out through another exhaust stack represented by *opening g*. Each zone of the building has a volume of 800 m^3.

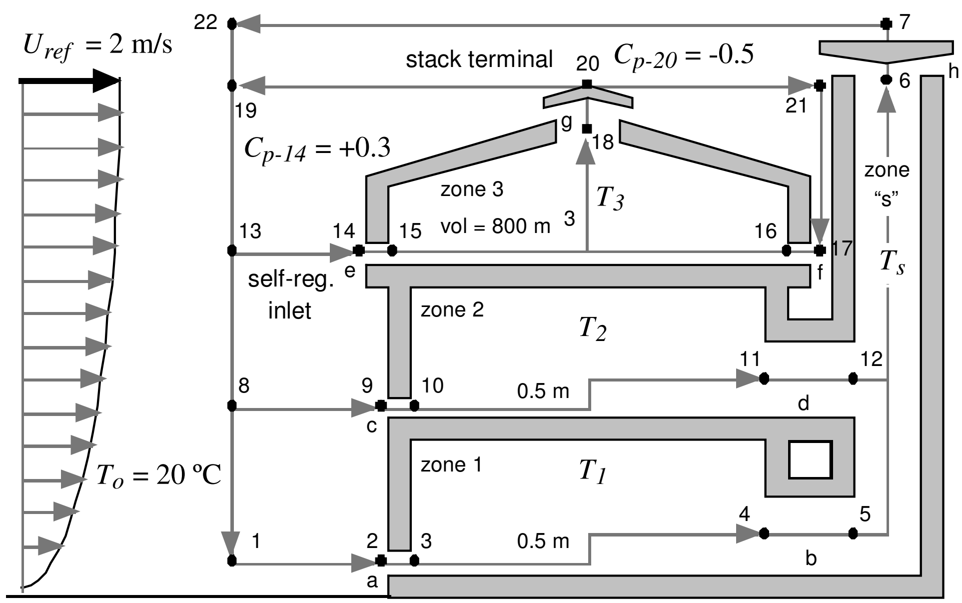


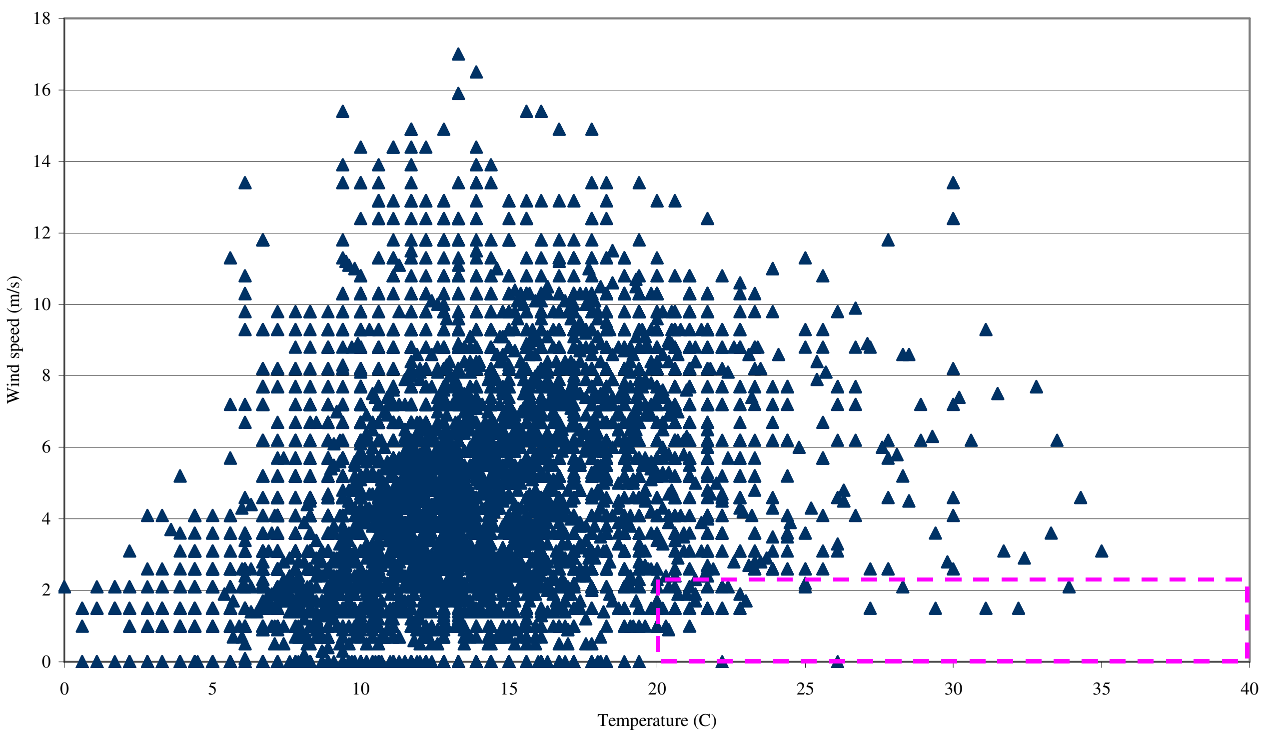
Figure 7 – Global geometry, topology, and pressure nodes for the ventilation flow loops of a building model based on the Inland Revenue Building, England (repeated from Figure 3.16 of Axley 2001)

4.2 Design Conditions and Criteria

In addition to the global geometry presented in Figure 7, the designer must select indoor temperatures, outdoor temperature, wind speed, wind pressure coefficients, and ventilation flow rates to perform the design analysis. It is not obvious what values to select for many of these parameters. For example, it may not be sensible to select extremes (e.g., very low wind speed) for the design ambient conditions. Such extremes may rarely occur or may prove too severe a challenge for a pure natural ventilation system. For many U.S. climates, it may be necessary to either tolerate limited periods during which indoor environmental conditions will be outside design conditions considered typical for conventional, mechanically conditioned buildings or to provide some supplemental mechanical systems (i.e., a hybrid ventilation system) for such periods. That said, the procedure followed below provides a realistic example problem only and is not being proposed as formal guidance for determining design conditions for natural ventilation systems. Emmerich, Dols, and Axley [1] described a simple method to evaluate the suitability of a given climate to cool a commercial building with natural ventilation and went on to apply that method to ten California locations. That analysis indicated that the coastal climates of California are well suited to natural ventilation with respect to climatic considerations. Therefore, the building described above will be situated in San Francisco for the purposes of this sample application of LoopDA. Per the earlier climate suitability analysis, a natural ventilation system could potentially cool a commercial building with combined solar and internal heat gains of 10 W/m^2 to 80 W/m^2 greater than 90 % of the hours of the year with a supplemental night cooling system expected to be effective for any days that would be overheated based on direct ventilative cooling alone. Assuming a heat gain rate of 20 W/m^2 (a low but achievable design target), the required average ventilation rate is 2.2 h^{-1} with a standard deviation of 2.6 h^{-1}. Therefore, a design ventilation rate of 5 h^{-1} (or about one standard deviation above the average) is a reasonable design objective for summer cooling. The coincident design indoor temperature for this summer condition may be selected as 26 ºC (based on the high end of ASHRAE's summer thermal comfort zone [5]).

Figure 8 shows the hourly outdoor temperatures and coincident wind speeds for the San Francisco TMY2 weather file [7]. From Figure 8, it appears conservative to choose an outdoor temperature of 20 ºC with a wind speed of 2 m/s for the design conditions as hours with both higher temperatures and lower wind speeds are rare as shown by the dashed box.

Although it is typical to use a wind pressure profile that is dependent on wind direction (and possibly



relative location of an opening on a wall), a single design value will be chosen for this example assuming the building will be oriented to take advantage of prevailing wind direction. Per Figure 16.7 of the ASHRAE Handbook of Fundamentals [5], a surface average wind pressure coefficient of 0.3 will be selected for the ventilation openings in the walls. Per Figure 16.9 of the ASHRAE Handbook of Fundamentals [5], a single value of -0.5 will be used for the wind pressure coefficient on the exhaust stacks.

Loop2

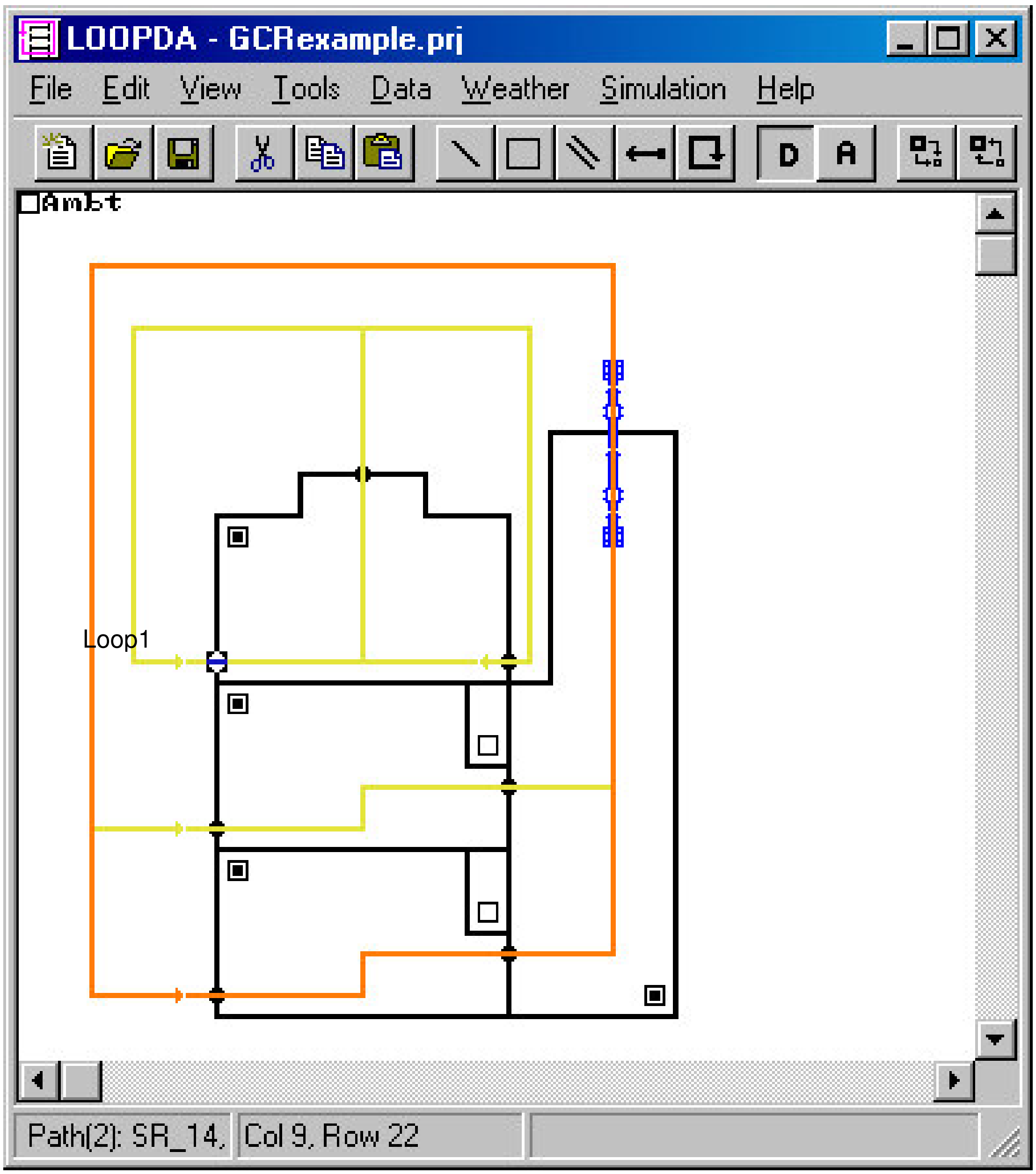
Figure 8 – Wind speeds vs. outdoor temperatures for San Francisco TMY2 weather file

4.3 Pressure Loops

With the building geometry and design conditions established, one may use LoopDA to form the loop equations and size the various natural ventilation system components. Figure 9 shows the LoopDA Sketchpad representation of the building elevation with the four pressure loops that must be analyzed. Loops 1 and 4 are equivalent loops following nodes 13-14-15-18-20-19-13 and nodes 21-17-16-18-20-21 serving *zone 3* (per Figure 7). Loop 2 follows nodes 8-9-10-11-12-6-7-22-8 serving *zone 2* and Loop 3 follows nodes 1-2-3-4-5-6-7-22-1 serving *zone 1*.

Loop3

Figure 9 – LoopDA Sketchpad representation of natural ventilation design sample problem



4.3.1 Loops 1 & 4

Loops 1 and 4 are equivalent loops each providing 0.55 m^3/s (half of the design 5 h^{-1}) to *zone 3* via self-regulating inlet vents. Both loops exhaust through the *stack terminal g* on Figure 7 for a total design flow of 1.1 m^3/s through the stack terminal. The self-regulating inlet vents are modeled in LoopDA as power law flow elements with an exponent of 0.1 (see Axley 2001 for more information) and an undetermined characteristic design parameter (CDP) C_e (see Figure 10). The stack terminal is modeled as an orifice with the area $A_{orfc,g}$ (referred to as *Aorfc1* by LoopDA) as the CDP. The complete pressure loop properties from LoopDA are shown in Figure 11.

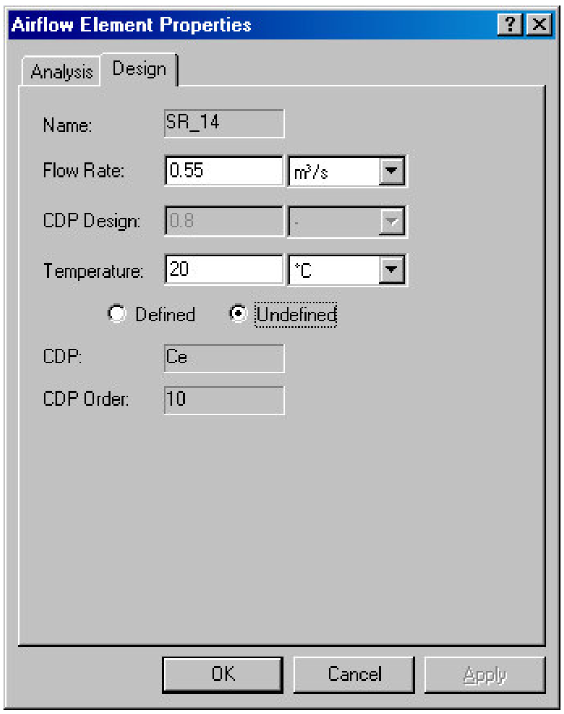


Figure 10 – Airflow element design window for the self-regulating inlet vent of Loop 1

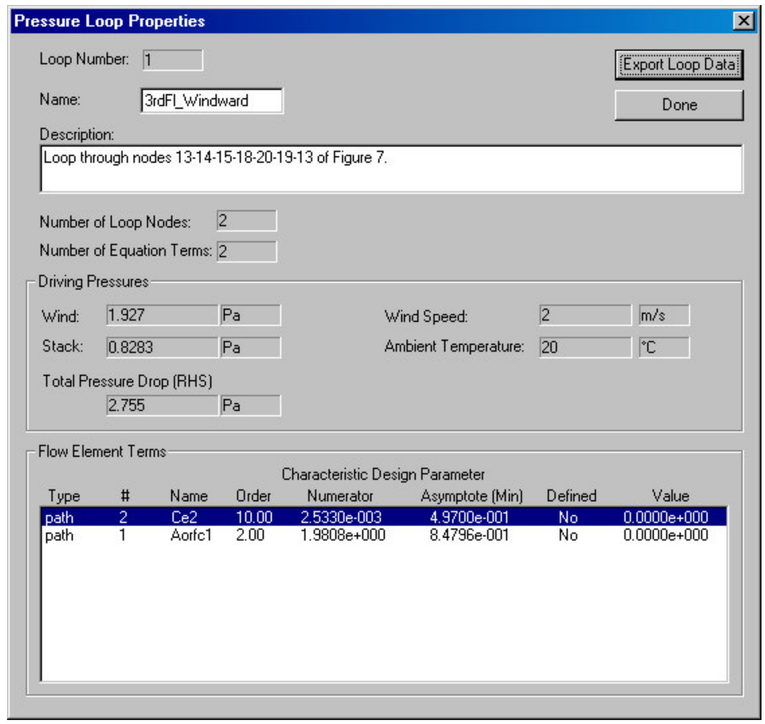
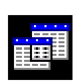


Figure 11 – Pressure loop properties window for Loop 1

After entering the information for Loop 1, the loop data are exported to a tab-delimited file that is pasted into the LoopDA spreadsheet template (click the icon below to view the Loop 1 information as it appears after being pasted into the LoopDA template).



LOOPDA Loop1
Worksheet

Since Loop 1 has only two elements with undetermined CDPs, the LoopDA template plot is simple and shows the sizing relationship between C_e and $A_{orfc,g}$ (see Figure 12). From Figure 12, the CDP for either element may be chosen (based on other considerations such as available component sizes from catalog data) and the minimum required size for the other CDP is fixed. For this example, selecting a value of 0.8 for C_e dictates a minimum orifice area of 0.85 m^2 which might be rounded up to 1.0 m^2 based on availability.

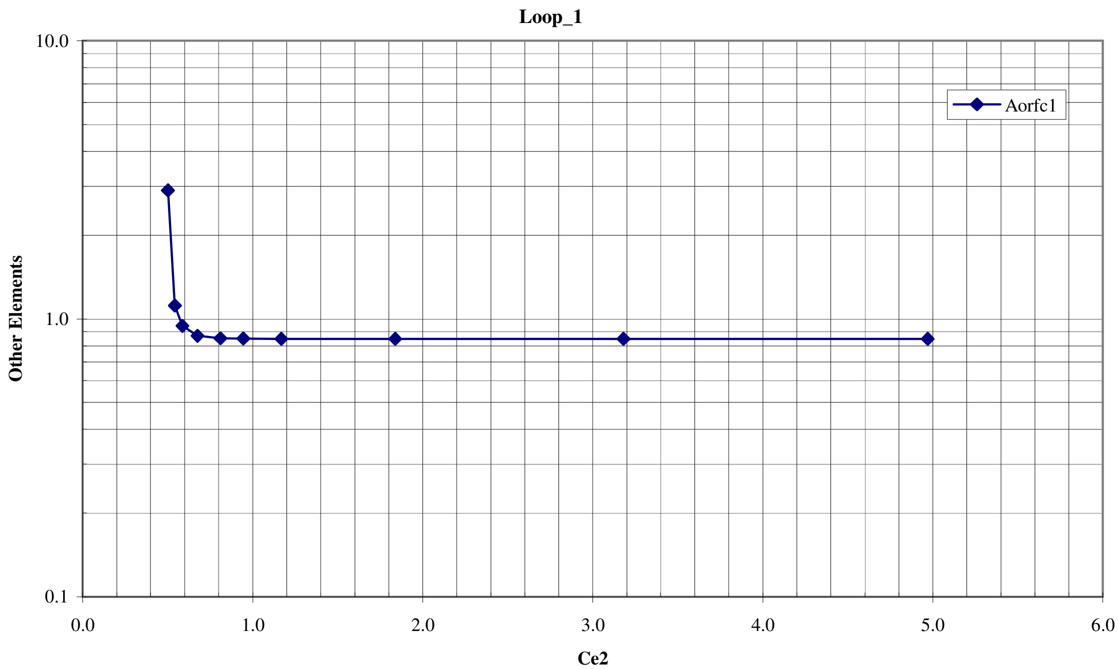


Figure 12 – Asymptotic relationship between CDP of self-regulating inlet vent Ce (Ce2) and CDP of stack terminal $A_{orfc,g}$ (Aorfc1) for Loop 1

4.3.2 Loop 2

Loop 2 supplies 1.1 m^3/s (i.e., 5 h^{-1}) to *zone 2* via *inlet c* on Figure 7. The flow exhausts through *outlet d* into the stack zone s and out the *stack terminal h* on Figure 7. Note that the stack must also exhaust the ventilation flow from *zone 1* for a total design flow of 2.2 m^3/s through the stack. The inlet and outlet vents are modeled in LoopDA as orifice flow elements with $A_{orfc,c}$ (*Aorfc5*) and $A_{orfc,d}$ (*Aorfc4*) as the undetermined CDPs. The stack is modeled using a Darcy-Colebrook duct model with an orifice as the inlet (the CDP is the area *A3*), an orifice as the outlet (the CDP is *A1*), and a 1m long round duct segment (the CDP is the duct diameter *D3*). The complete pressure loop properties from LoopDA are shown in Figure 13. Note that, if desired, the user must impose the condition that the stack orifice areas be based on the duct diameter during the sizing process as LoopDA treats them as independent CDPs.

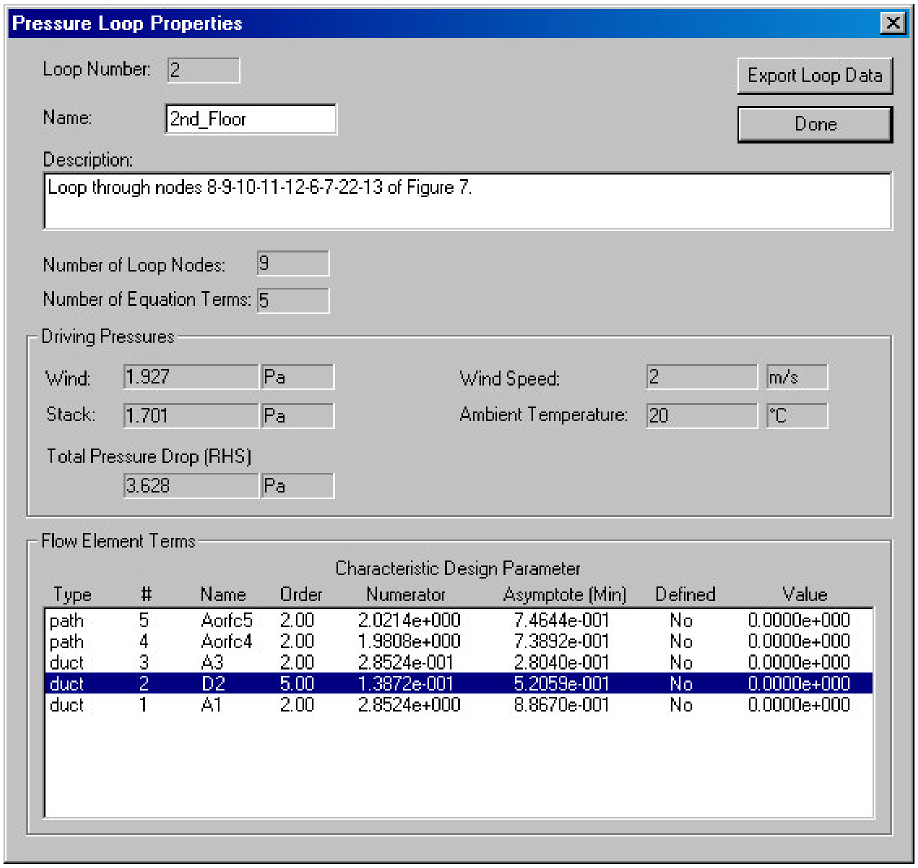
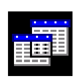


Figure 13 – Pressure loop properties window for Loop 2

After entering the information for Loop 2, the loop data are exported to a tab-delimited file which is pasted into the LoopDA spreadsheet template (click the icon below to view the Loop 2 information as it appears after being pasted into the LoopDA template).



LoopDA Loop
Worksheet1

Loop 2 has only five elements with undetermined CDPs (although *D2*, *A1*, and *A3* are related). Figure 14 from the LoopDA template plot shows the sizing relationship between *D2* and all other CDPs. From Figure 14, *D2* will be set at 1.2 m. Basing the stack inlet and outlet areas (*A1* and *A3*) on this diameter sets these areas at 1.1 m^2 (which is larger than the minimum requirements for these areas per the Loop 2 worksheet and Figure 14).

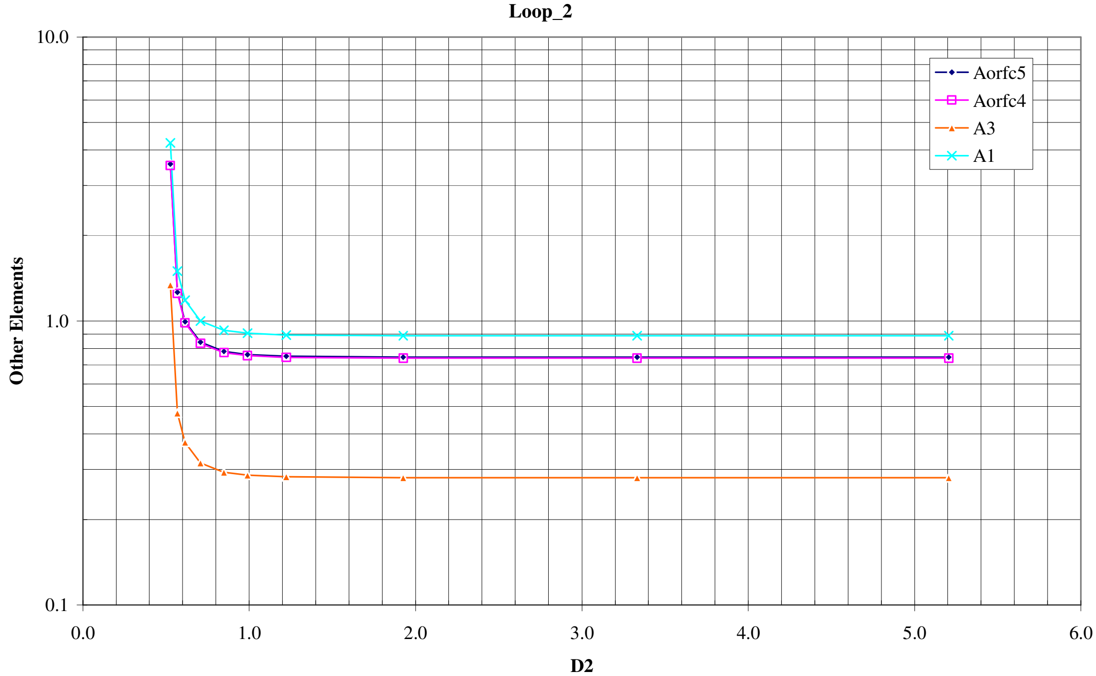


Figure 14 – Asymptotic relationships for Loop 2

Unlike Loop 1, Loop 2 still has undetermined CDPs. Returning to the LoopDA sketchpad, entering the parameters established for the stack duct and terminals (*D2*, *A1* and *A3*), and exporting Loop 2 (see Figure 15 for the pressure loop properties) for a second time yields a second worksheet for this loop (click the icon below Figure 15 to view).

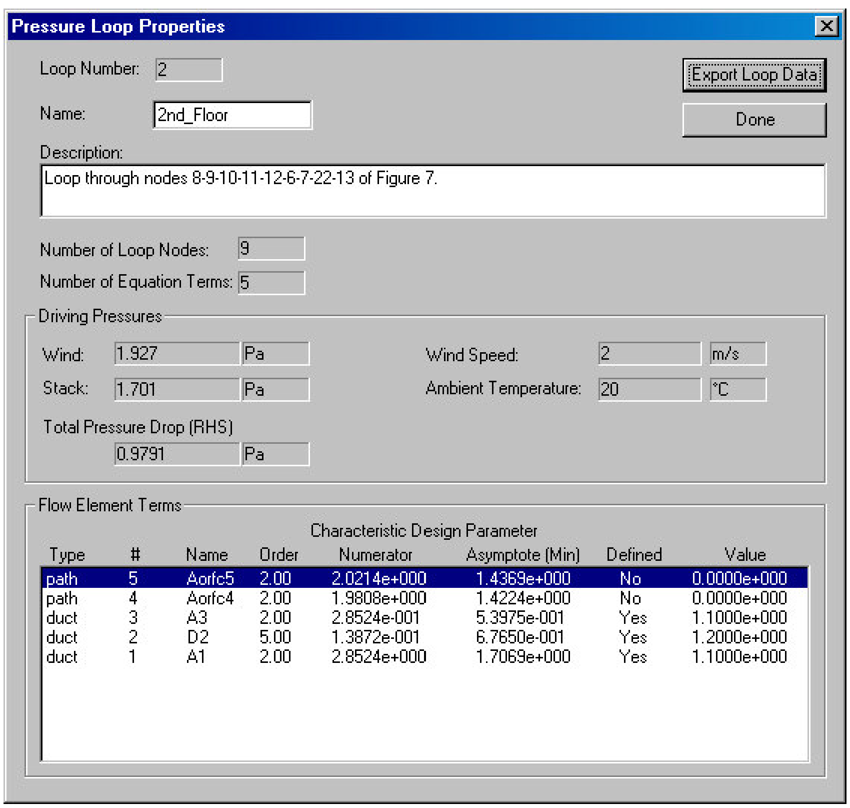


Figure 15 – Loop 2 pressure loop properties after setting the sizes of D2, A1 and A3

LoopDA Loop 2
Worksheet2

As seen in the worksheet and Figure 15, $A_{orfc,c}$ (*Aorfc5*) and $A_{orfc,d}$ (*Aorfc4*) remain to be selected. Figure 16 shows the asymptotic relationship between these remaining undetermined CDPs. From Figure 16, the inlet *Aorfc5* will be selected as 2.0 m^2, which sets the minimum outlet *Aorfc4* also at approximately 2.0 m^2.

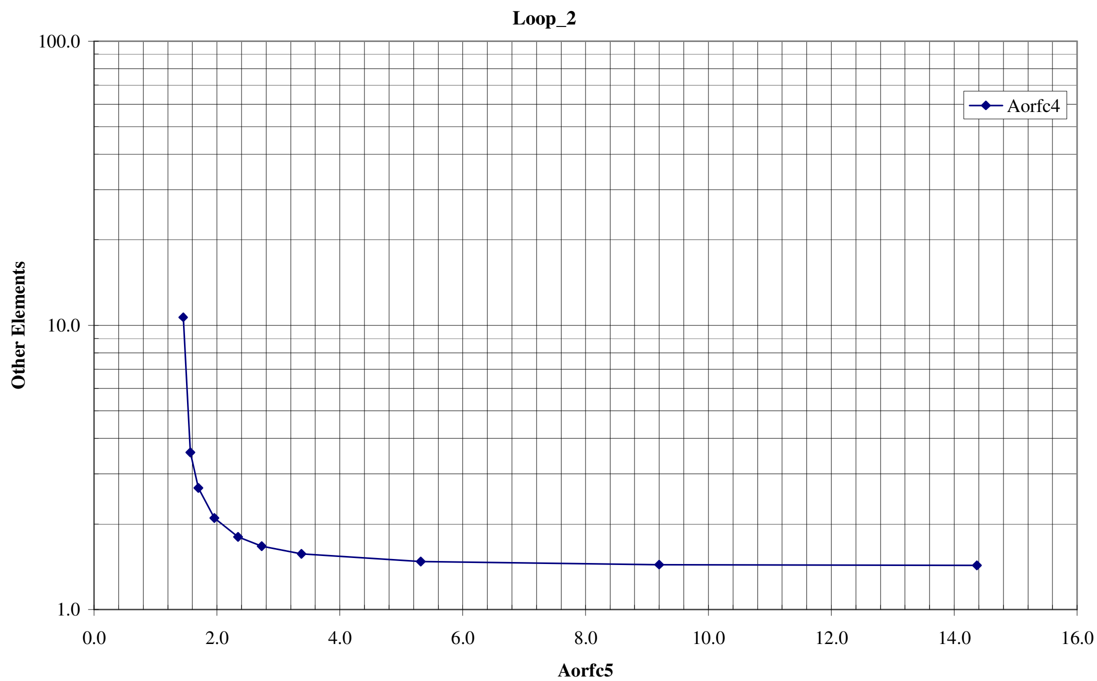


Figure 16 – Asymptotic relationship of remaining undetermined CDPs for Loop 2

4.3.3 Loop 3

Loop 3 consists of the same type of elements as Loop 2 – *inlet orifice a* (*Aorfc7*), *outlet orifice b* (*Aorfc6*), and the shared *stack exhaust g*. As seen in Figure 17, the previously defined stack CDPs are retained leaving only the inlet and outlet of *zone 1* to be defined. The LoopDA spreadsheet is similar to the second Loop 2 worksheet (click below to view). The asymptotic relationship between the undetermined CDPs *Aorfc6* and *Aorfc7* is shown in Figure 18. Selecting the outlet to be the same as for *zone 2* at 2.0 m^2 sets the minimum size for the inlet *Aorfc7* at approximately 1.3 m^2.

LoopDA Loop 3
Worksheet

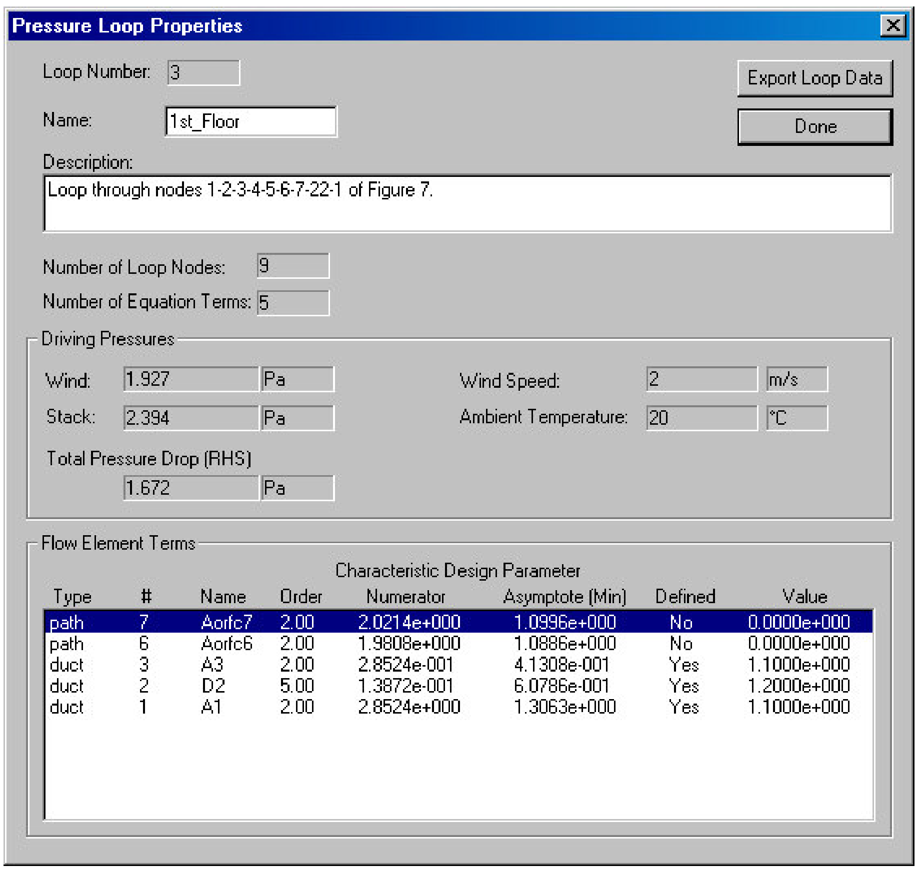


Figure 17 – Pressure loop properties window for Loop 3

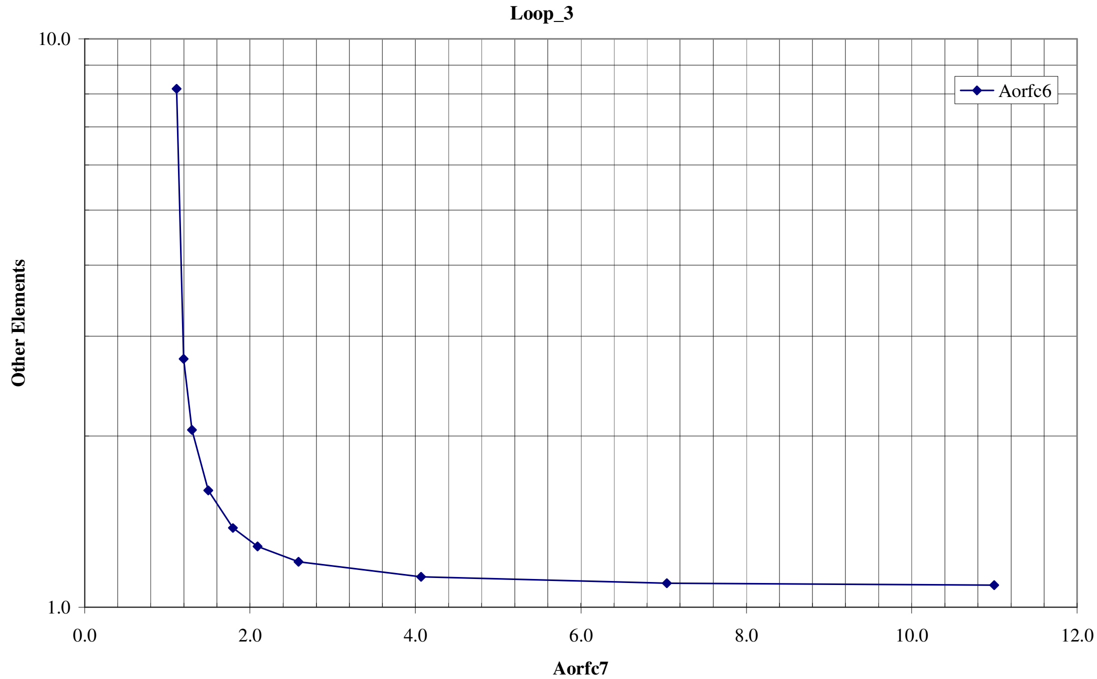


Figure 18 – Asymptotic relationships for Loop 3

4.3.4 Design Summary and Analysis

The completed design of the four ventilation loops is summarized below in Table 1.

Loop	Element	CDP		Size
		Figure 7	LoopDA	
1	Self-regulating inlet vent	C_e	Ce2	0.80
1	Stack terminal	$A_{orfc,g}$	Aorfc1	1.00
2	Inlet	$A_{orfc,c}$	Aorfc5	2.00
2	Outlet	$A_{orfc,d}$	Aorfc4	2.00
2	Stack inlet	$A_{stack\ in}$	A3	1.13
2	Stack diameter	$D_{stack\ duct}$	D2	1.20
2	Stack outlet	$A_{stack\ term}$	A1	1.13
3	Inlet	$A_{orfc,a}$	Aorfc7	1.30
3	Outlet	$A_{orfc,b}$	Aorfc6	2.00
3	Stack inlet	$A_{stack\ in}$	A3	1.13
3	Stack diameter	$D_{stack\ duct}$	D2	1.20
3	Stack outlet	$A_{stack\ term}$	A1	1.13
4	Self-regulating inlet vent	C_e	Ce3	0.80
4	Stack terminal	$A_{orfc,g}$	Aorfc1	1.00

Table 1 – Design values of sized components

LoopDA may now be used to analyze the completed design by performing simulations ranging from steady state under non-design conditions to a seasonal or annual analysis using TMY2 or other weather data for the location. One condition that could be analyzed is the potential for excess outdoor airflow under a winter condition. Referring back to Figure 8, an outdoor temperature of 5 ºC and a wind speed of 8 m/s will be used. Also, the wall opening wind pressure coefficients will be increased to 0.6 to increase the impact of wind for this case. The indoor temperature is set to 20 ºC for this case.

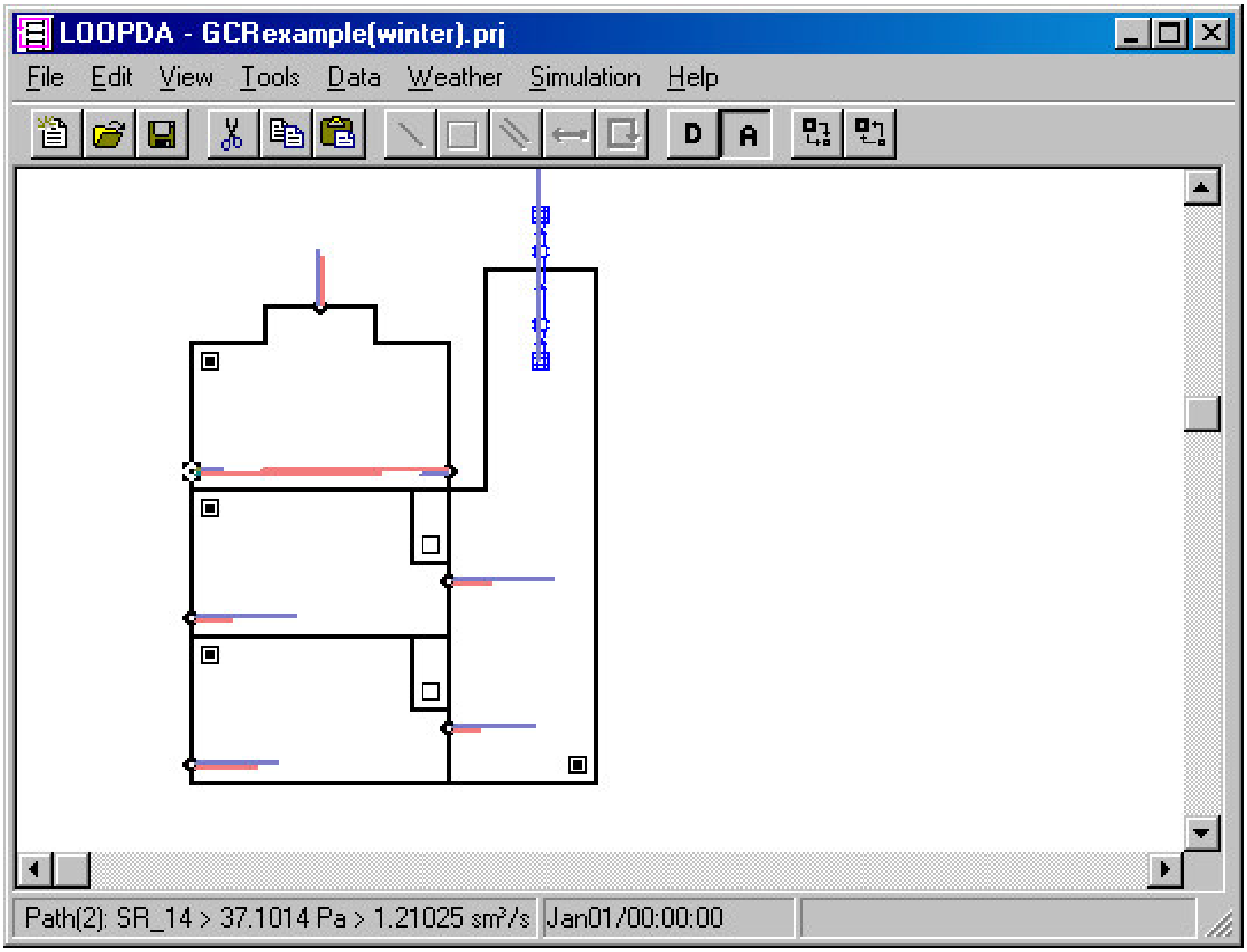


Figure 19 – Simulation results for winter condition analysis. Blue lines indicate direction and relative magnitude of airflow (note: status bar indicates a flow of 1.21 sm^3/s for the self-regulating inlet vent)..

The results of the design analysis of a winter condition are shown in Figure 19. This analysis shows the risk of greatly over ventilating the space if no provision is made for altering the ventilation openings under a winter operating condition as the flow into zones 1 and 2 increases to 3 to 4 times the design flow. The self-regulating inlets perform better but the outdoor airflow still doubles from the design case. For a real building, the designer would likely specify a desired minimum winter ventilation flow and then use LoopDA in design mode to determine desired vent opening sizes in a winter mode. An operational strategy could then be established whereby, for example, half of the openings are used during winter operation.

5 CONCLUSION

This version of LoopDA was developed to demonstrate the implementation of the *Loop Equation Design Method* within an existing multi-zone modeling environment. It will serve to provide designers with a framework for implementing the design method in order to become familiar with the method, to explore the practicality of using this method within the overall natural ventilation system design process, and to provide feedback to the developers as to the potential for this tool for use by the design and analysis community.

As this is a preliminary version, it is reasonable that the potential for enhancements exists. Some potential enhancements have already been identified including: the implementation of a more diverse set of inverse flow component types, more robust user interface features and consideration for the design of mechanical components of hybrid ventilation systems. In general, inverse airflow elements are relatively easy to add to the existing environment. However, depending on the element type, the inverse solution to sizing some elements could prove to be more difficult than others, e.g., a polynomial fan curve. The user interface could perhaps be improved by eliminating the need for the external spreadsheet; providing automated population of analysis components based on design component sizes; verifying continuity of flow through components serving multiple loops; generation of reports summarizing design conditions and system design, enabling the application of a more diverse set of design constraints, e.g., requiring duct inlet, outlet and segments of the same size or providing a direct means to consider infiltration.

6 REFERENCES

1. Emmerich, S.J., W.S. Dols, and J.W. Axley. *Natural Ventilation Review and Plan for Design and Analysis Tools*. NISTIR 6781, National Institute of Standards and Technology. 2001.
2. Dols, W.S. and G.N. Walton. *CONTAMW 2.0 User Manual*. National Institute of Standards and Technology. DRAFT 2002.
3. Axley, J.W. *Application of Natural Ventilation for U.S. Commercial Buildings*. GCR-01-820 NISTIR 6781, National Institute of Standards and Technology. 2001.
4. Axley, J.W. *Residential Passive Ventilation Systems: Evaluation and Design*. AIVC Technical Note 54. Coventry, AIVC.
5. ASHRAE 2001. *ASHRAE Handbook - 2001 Fundamentals*, Atlanta, GA.
6. Irving, S. and E. Uys. *CIBSE Applications Manual: Natural Ventilation in Non-domestic Buildings*. 1997, CIBSE: London.
7. Marion, W. and K. Urban. *User's Manual for TMY2s*. National Renewable Energy Laboratory, 1995.

7 ACKNOWLEDGMENTS

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NISTIR 7062

Impact of Natural Ventilation Strategies and Design Issues for California Applications, Including Input to ASHRAE Standard 62 and California Title 24

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ABSTRACT

Natural ventilation has the potential to reduce the energy required for cooling and ventilating commercial buildings while still providing acceptable thermal comfort and indoor air quality. While a recent surge of interest in Europe has advanced natural ventilation technology, much work is needed to realize this potential in California and the rest of the U.S. This report discusses the impact of natural ventilation strategies and design issues for California applications and provides input to ASHRAE Standard 62 and California Title 24 based on research performed by NIST that has been previously reported (Emmerich et al. 2001 and Dols and Emmerich 2002), additional work completed recently by NIST for the California Energy Commission, other completed and ongoing research by NIST, and other recent published literature. One area identified as a key to the realization of the potential advantages of natural ventilation is the emergence of hybrid natural and mechanical system strategies. The report provides recommendations for additional research and technology transfer to further advance application of natural ventilation to commercial buildings.

Key Words: analysis, design, energy efficiency, indoor air quality, modeling, natural ventilation, thermal comfort, ventilation.

DISCLAIMER

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1. INTRODUCTION

1.1 Background

Natural ventilation has the potential to significantly reduce the energy cost required for mechanical ventilation and cooling of commercial buildings. Natural ventilation approaches may reduce both first and operating costs compared to mechanical ventilation systems while maintaining adequate thermal comfort and ventilation rates that are consistent with acceptable or even superior indoor air quality (IAQ). Also, some studies have indicated that occupants reported fewer symptoms in buildings with natural ventilation compared to buildings with mechanical ventilation (Mendell et al. 1996). If natural ventilation can improve indoor environmental conditions, such improvements may also increase occupant productivity by reducing absenteeism, reducing health care costs, and improving worker productivity (Fisk and Rosenfeld 1997).

Because of these potential benefits, natural ventilation is being increasingly proposed as a means of saving energy and improving indoor air quality within commercial buildings, particularly in the "green" and "sustainable buildings" communities. These proposals are often made without any engineering analysis to support the claimed advantages, e.g., without calculating expected ventilation rates, air distribution patterns, or contaminant levels. In addition, proven design approaches have not been available in this country to incorporate natural ventilation into commercial building system designs. Natural ventilation strategies are less likely to reach the U.S. marketplace until design tools are made available and strategies are investigated and demonstrated for a variety of climates and construction types.

While natural ventilation is becoming more common in Europe, significant questions exist concerning its application in U.S. commercial buildings. These questions include the reliability of the outdoor air ventilation rates, distribution of this outdoor air within the building, control of moisture in naturally ventilated buildings, building pressurization concerns, and the entry of polluted air from outdoors. Some climates within California are well suited to natural ventilation, but these questions still must be addressed for these locales.

To help realize the potential benefits of natural ventilation in California, NIST has conducted a multi-year project for the California Energy Commission including a review of natural ventilation technology and strategies; exploration of the opportunities and issues of the application of natural ventilation related to climate, ambient air quality, and codes and standards; development of natural ventilation design methods and tools; and application of the tools and methods to several nonresidential building design projects as both a demonstration and investigation of issues for practicing design engineers.

1.2 Recent Developments

Research interest in natural ventilation system design and analysis has continued with numerous descriptions published at recent conferences such as Building Simulation 2003, Indoor Air 2002, ASHRAE meetings, and Roomvent 2002. Of particular relevance to natural ventilation in commercial buildings in California is a description of the design effort for a new federal office building being constructed in San Francisco that will utilize natural ventilation for both air quality and thermal comfort control. Haves et al. (2003) describes the design of this building including the use of both coupled thermal and airflow multizone and computational fluid dynamics simulations performed. The strategy employed was a wind-driven cross ventilation flow through a narrow, open-office floorplan in a high-rise tower. An estimate of potential energy cost savings of $9 million over 20 years has been reported for this building (EETD 2003).

Another recent development is the rapidly growing interest in hybrid ventilation systems (i.e., systems employing both natural ventilation and mechanical equipment to achieve thermal comfort and air quality control) both in the U.S. and throughout the world. Earlier NIST reports (Axley 2001 and Emmerich et al. 2001) highlighted the potential advantages of hybrid ventilation systems for U.S. applications and a major effort is underway via the International Energy Agency Annex 35 to develop and demonstrate hybrid ventilation systems in commercial buildings and methods and tools to support the design and analysis of such systems.

Natural ventilation offers the means to control air quality in buildings, to directly condition indoor air with cooler outdoor air, to indirectly condition indoor air by night cooling of building thermal mass, and to provide refreshing airflow past occupants when desired. However, the potential of natural ventilation systems depends, in part, on the suitability of a given climate, in part, on the design of the natural ventilation system used, and in part, on the advantages offered by mechanical system alternatives. As discussed below in Section 2, both climate and ambient air quality issues may limit the impact of 'pure' natural ventilation systems in California – either through the inability of a natural ventilation system to effect acceptable thermal comfort for significant time periods or through poor ambient air quality requiring air cleaning capabilities which may be difficult to implement in a natural ventilation system. Additionally, recent developments in natural ventilation system design have been matched by collateral developments in mechanical ventilation design. Recent reports of the design and performance of three U.K. buildings clearly indicate the advantages hybrid system may have when compared to both purely natural or purely mechanical ventilation alternatives (Arnold 2000; Braham 2000, Berry 2000).

Other potential advantages of hybrid ventilation over natural ventilation include better control of system performance and easier market acceptance in the U.S. Thus, the future for both natural and mechanical ventilation systems now appears to lie in the field of hybrid ventilation.

1.3 Contents

This report discusses the impact of natural ventilation strategies and design issues for California applications and provides input to ASHRAE Standard 62 and California Title 24 and addresses Task 4.4.3a and 4.4.3b of the CEC-EEB RMT project. The impacts and issues discussed are based on the research performed previously by NIST (Emmerich et al. 2001 and Dols and Emmerich 2002), additional work completed recently by NIST for the California Energy Commission, other completed and ongoing research by NIST, and recently published literature. This report is organized into three main sections – Impact of Natural Ventilation Strategies and Design Issues for California Applications, Potential Revisions to ASHRAE Standard 62 and California Title 24, and Additional Recommendations. The first section contains an overview of the potential impact and design issues relevant to the application of natural ventilation to small commercial buildings in California. The second section provides potential revisions to ASHRAE Standard 62 and California Title 24. The third section discusses additional recommendations including research and technology transfer needs.

2. IMPACT OF NATURAL VENTILATION STRATEGIES AND DESIGN ISSUES FOR CALIFORNIA APPLICATIONS

Two of the primary goals of the NIST research effort were to evaluate the potential impact of natural ventilation strategies in California applications and to identify relevant design issues. These impacts and issues reflect the lessons learned from the application of the tools and methods – specifically the loop equation design tool LoopDA - described in earlier NIST reports (Axley 2001, Axley et al. 2002, Emmerich et al. 2001, Dols and Emmerich 2003) in early phase design work for two nonresidential building design projects.

2.1 Impact of Natural Ventilation Strategies

A key intent of natural ventilation systems is the reduction of energy consumed to cool and ventilate buildings. However, these potential savings will vary widely depending on building type, climate and other factors. A climate suitability analysis was applied to a variety of California climates to assess the potential application of natural ventilation for commercial buildings with a range of internal gains. Since natural ventilation systems directly affect building ventilation systems and rates, they will impact indoor air quality and thus have the potential to impact occupant comfort, health, and productivity. Therefore, this section also discusses the impact of natural ventilation strategies on indoor air quality.

2.1.1 Climate Suitability

In earlier work for the California Energy Commission (Emmerich et al. 2001), NIST developed a climate suitability analysis technique to evaluate the potential of a given location for direct ventilative cooling and complimentary nighttime ventilative cooling (i.e., of a building's thermal mass). The direct ventilative cooling may be provided by either a natural ventilation system or a fan-powered economizer system. As such, it is a useful pre-design analytical technique. It also establishes preliminary estimates of design ventilation rates needed for preliminary design calculations (i.e., given knowledge of the likely internal gains in a building and local climatic conditions). Specifically, with it a designer may estimate the ventilation rate needed to offset internal gains when direct ventilation can be effective and the internal gains that may be offset by nighttime ventilation when direct ventilation will not work. However, since the technique depends on no building-specific information other than estimated thermal loads, the technique may be applied to evaluate the potential impact of natural ventilation in a given climate for buildings with a range of thermal loads.

The climate suitability analysis technique is based on a general single-zone thermal model of a building configured and operated to make optimal use of direct and/or nighttime ventilative cooling. With this model in hand, an algorithm was defined to process hourly annual weather data, using well-established thermal comfort criteria, to complete the evaluation. The details of this approach were presented in earlier NIST reports (Axley 2001, Emmerich et al. 2001, Axley and Emmerich 2002).

To evaluate the potential impact of natural ventilation strategies for small commercial buildings in California, this method was applied to the ten California locations with available TMY2 hourly annual climatic data (Marion and Urban 1995). While the ten locations, listed in Table 1 below, do not statistically represent the state in terms of population or climate, they do include both coastal and inland climates that cover much of the latitudinal range of the state. Calculations were made for buildings with total internal thermal gains ranging from 10 W/m^2 to 80 W/m^2.

Table 1 California locations used for initial climate suitability evaluation.

Coastal	Inland
San Diego	*Daggett*
Long Beach	*Bakersfield*
Los Angeles	*Fresno*
Santa Maria	*Sacramento*
San Francisco	
Arcata	

Computed results follow in Table 2 and 3. Data in this table is organized in two sets – a set of four columns that report the direct ventilative cooling results:

- the average air change rate required to effect direct ventilative cooling for each of four specific internal gain rates for each of the ten California locations – *when direct cooling is effective*,
- the variation of the air change rate about the average value to be expected for each case – as indicated by the standard deviation of the ventilation rates computed to achieve thermal comfort,
- the fraction of the year direct cooling is effective for each case – i.e., the number of hours direct ventilation is effective out of the 8760 h in a year's record, and
- the fraction of the year when heating is expected to be needed ;

and a final column that reports the results for complimentary night cooling:

- the average specific internal gain that can be offset by a nominal unit air change rate of (previous) nighttime cooling for overheated days (i.e., those days when direct ventilative cooling is not effective for all hours from 6 a.m. to 6 p.m.),
- the fraction of overheated days that may, potentially, be cooled using nighttime ventilation, and
- the total number of days during the year that nighttime cooling may, potentially, be effective.

These statistics have been devised to provide guidance for preliminary design considerations. In the present implementation, simple mean values and standard deviations were computed to characterize the range of ventilation rates required. As the distribution of needed ventilation rates may not reflect a Gaussian distribution, some of the tabulated values indicate "negative" ventilation rates will be required at times (e.g., 3.4 h^{-1} ± 8.7 h^{-1}). These exceptional values should not be taken literally – the needed ventilation rate will never be less than zero. A future implementation of the climate suitability method, using appropriate statistical analysis, would correct these minor but physically inconsistent results. Results in white or light gray boxes will require, on average, ventilation rates in the 0 h^{-1} to 5 h^{-1} and 5 h^{-1} to 10 h^{-1} ranges respectively – both quite reasonable using commonly available natural ventilation strategies. Results in medium and darker gray (10 h^{-1} to 15 h^{-1} and above 15 h^{-1}) will be more difficult to achieve using available natural ventilation strategies.

For example, the Bakersfield results show that an average ventilation rate of 3.4 h^{-1} ± 8.7 h^{-1} may be expected to provide direct ventilative cooling when the internal gain is 10 W/m^2 (3.2 $Btu/ft^2 \cdot h$). Furthermore, for this location, direct ventilative cooling may be expected to be useful 64 % of the hours of the year for this same specific internal gain. Nighttime cooling can be used in this climate to compliment direct cooling for 93 days of the year that accounts for 94 % of the expected overheated days. Thus 6 % of these overheated days (approximately 11 days) would require mechanical air conditioning to achieve thermal comfort in a typical year. During the 159 days with possible nighttime ventilative cooling, internal gains can be offset at the rate of 3.2 $W/m^2 \cdot h^{-1}$ ± 2.6 $W/m^2 \cdot h^{-1}$

($1.0\ Btu/ft^2h \cdot h^{-1} \pm 0.81\ Btu/ft^2h \cdot h^{-1}$). Thus to offset a specific internal gain of 10 W/m^2 ($3.2\ Btu/ft^2 \cdot h$), the average nighttime ventilation rate would have to be $10 \div 3.2 \geq 3.1\ h^{-1}$. (Here, the ≥ sign is used as the computation is based on the assumption that the building is thermally massive.)

Table 2 Climate suitability statistics for coastal California locations

	Direct Cooling				Night Cooling[1]
	10 W/m^2	20 W/m^2	40 W/m^2	80 W/m^2	
Arcata					
Vent. Rate or Cooling Potential	1.1 ±0.4 h^{-1}	1.7 ±0.8 h^{-1}	3.3 ±1.7 h^{-1}	6.7 ±3.4 h^{-1}	10.5 ±1.5 $W/m^2 \bullet h^{-1}$
% Effective[2]	74 %	100 %	100 %	100 %	100 % (2 d)
% Heating	26 %	0 %	0 %	0 %	
Long Beach					
Vent. Rate or Cooling Potential	2.3 ±5.6 h^{-1}	4.4 ±11.1 h^{-1}	8.7 ±22.1 h^{-1}	17.4 ±44.3 h^{-1}	6.2 ±2.7 $W/m^2 \bullet h^{-1}$
% Effective[2]	88 %	91 %	91 %	91 %	92 % (95 d)
% Heating	3 %	0 %	0 %	0 %	
Los Angeles					
Vent. Rate or Cooling Potential	1.7 ±1.9 h^{-1}	3.3 ±3.8 h^{-1}	6.6 ±7.7 h^{-1}	13.2 ±15.4 h^{-1}	6.6 ±2.2 $W/m^2 \bullet h^{-1}$
% Effective[2]	96 %	97 %	97 %	97 %	100 % (55 d)
% Heating	1 %	0 %	0 %	0 %	
San Diego					
Vent. Rate or Cooling Potential	1.8 ±3.3 h^{-1}	3.6 ±6. h^{-1}	7.2 ±13.0 h^{-1}	14.5 ±26.1 h^{-1}	3.6 ±2.3 $W/m^2 \bullet h^{-1}$
% Effective[2]	91 %	92 %	92 %	92 %	90 % (52 d)
% Heating	1 %	0 %	0 %	0 %	
San Francisco					
Vent. Rate or Cooling Potential	1.3 ±1.3 h^{-1}	2.2 ±2.6 h^{-1}	4.5 ±5.1 h^{-1}	8.9 ±10.3 h^{-1}	8.6 ±2.6 $W/m^2 \bullet h^{-1}$
% Effective[2]	90 %	99 %	99 %	99 %	100 % (12 d)
% Heating	10 %	0 %	0 %	0 %	
Santa Maria					
Vent. Rate or Cooling Potential	1.4 ±1.8 h^{-1}	2.4 ±3.4 h^{-1}	4.9 ±6.9 h^{-1}	9.7 ±13.8 h^{-1}	11.2 ±2.8 $W/m^2 \bullet h^{-1}$
% Effective[2]	82 %	99 %	99 %	99 %	100 % (17 d)
% Heating	17 %	0 %	0 %	0 %	

Table 3 Climate suitability statistics for inland California locations

	Direct Cooling				Night Cooling[1]
	10 W/m^2	20 W/m^2	40 W/m^2	80 W/m^2	
Bakersfield					
Vent. Rate or Cooling Potential	3.4 ±8.7 h^{-1}	5.7 ±16.1 h^{-1}	11.5 ±32.2 h^{-1}	22.9 ±64.3 h^{-1}	3.2 ±2.6 W/m^2•h^{-1}
% Effective[2]	64 %	77 %	77 %	77 %	94 % (159 d)
% Heating	12 %	0 %	0 %	0 %	
Daggett					
Vent. Rate or Cooling Potential	3.4 ±8.9 h^{-1}	5.8 ±16.5 h^{-1}	11.6 ±32.9 h^{-1}	23.2 ±65.8 h^{-1}	3.7 ±2.9 W/m^2•h^{-1}
% Effective[2]	60 %	71 %	71 %	71 %	86 % (169 d)
% Heating	11 %	0 %	0 %	0 %	
Fresno					
Vent. Rate or Cooling Potential	2.9 ±7.2 h^{-1}	4.6 ±12.8 h^{-1}	9.2 ±25.6 h^{-1}	18.3 ±51.1 h^{-1}	4.3 ±2.8 W/m^2•h^{-1}
% Effective[2]	63 %	81 %	81 %	81 %	100 % (161 d)
% Heating	18 %	0 %	0 %	0 %	
Sacramento					
Vent. Rate or Cooling Potential	2.3 ±6.5 h^{-1}	3.8 ±11.6 h^{-1}	7.6 ±23.2 h^{-1}	15.1 ±46.4 h^{-1}	7.0 ±2.2 W/m^2•h^{-1}
% Effective[2]	69 %	88 %	88 %	88 %	100 % (142 d)
% Heating	19 %	0 %	0 %	0 %	

[1] Night cooling for days when direct cooling is not effective.

[2] For direct cooling % = hours effective ÷ 8760 h; for night cooling % = days effective ÷ days needed.

white = 0 h^{-1} to 5 h^{-1}

light gray = 5 h^{-1} to 10 h^{-1}

medium gray = 10 h^{-1} to 15 h^{-1}

dark gray > 15 h^{-1}

The data presented in Table 2 and 3 have been plotted in the form of *bubble* plots for the six coastal locations and the four inland locations – Figure 1 and Figure 2. In these plots the center of each bubble locates the average ventilation rate required for each of the four specific internal gain rates considered and the size of the bubble indicates the relative efficacy of direct ventilative cooling. Thus larger bubbles located lower in the plot indicate direct ventilative cooling is not only feasible (vis a vis ventilation rate required) but also effective.

As might be expected, Table 2 and Figure 1 show that natural ventilation strategies could have a very significant impact in California. Specifically, the coastal climates of California are very well suited to natural ventilation with respect to climatic considerations. For most of these locations, the direct ventilative cooling approaches 90 % to 100 % effectiveness with most of the ineffective hours representing either times when heating is required or times that could be cooled through night ventilative cooling. Equally significant is the fact that, for buildings with moderate internal gains in most of these locations, the required cooling can be achieved with very achievable average air change rates of about 5 h^{-1} or less. Additionally, with the exception of Long Beach, the required air change rates have reasonable standard deviations less than or about equal to the averages. The required air change rates for the buildings with higher internal loads may be achievable with new and developing natural ventilation technology.

On the other hand, natural ventilation is less promising for the hotter, more humid climates of inland California. As shown in Table 3 and Figure 2 for the four inland locations, both direct and night ventilative cooling have a lower percentage effectiveness and require larger air change rates (with much larger standard deviations) then for the coastal locations. Despite that, a significant ventilative cooling potential exists for these locations. However, some type of hybrid system with mechanical cooling may be more successful in these situations.

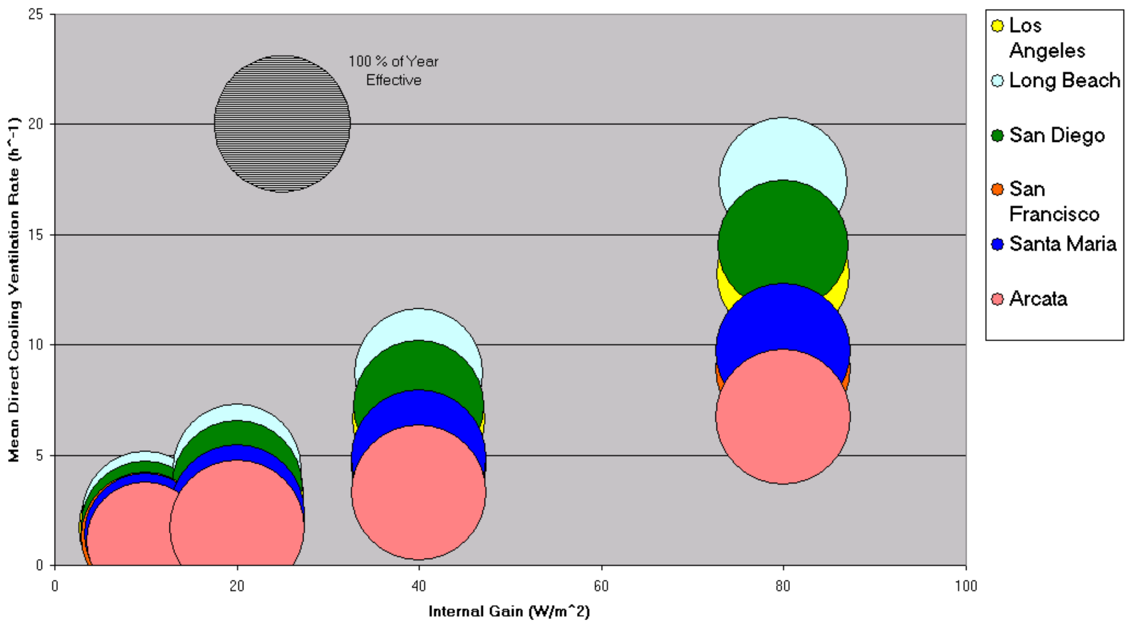

Figure 1 Potential impact of natural ventilation for coastal California locations.

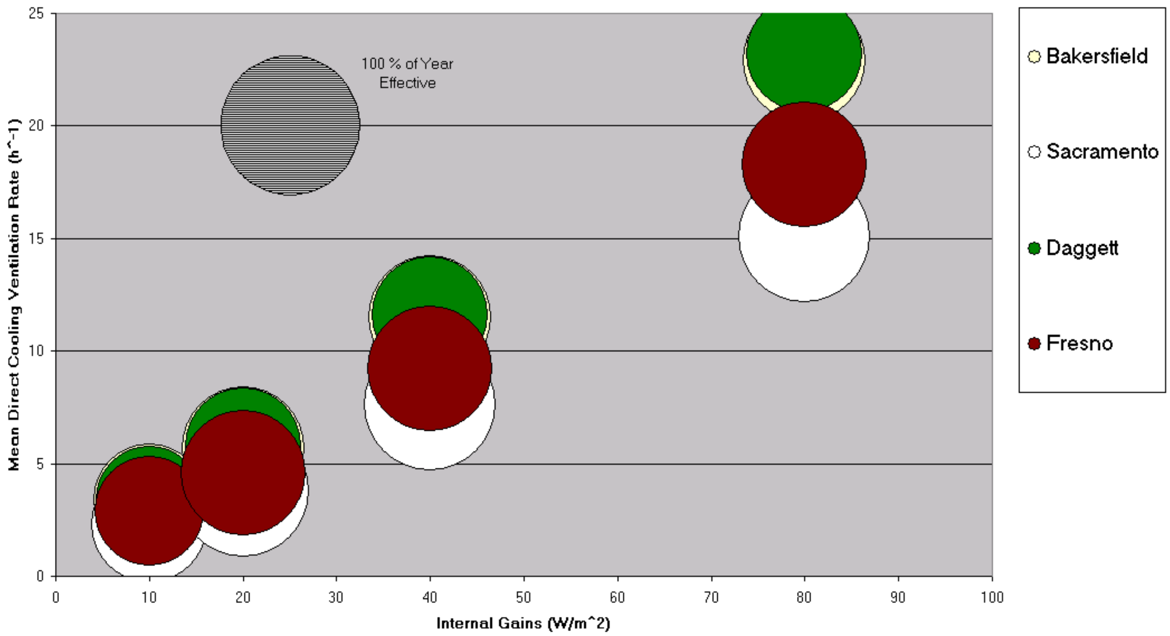

Figure 2 Potential impact of natural ventilation for the inland California locations

2.1.2 Indoor Air Quality Impacts

Since natural ventilation systems directly affect building ventilation systems and rates, they will impact indoor air quality and the potential exists to have a significant impact on occupant comfort and productivity. That impact could be either positive or negative depending on the natural ventilation system design, installation, operation and maintenance. Also, the actual health, comfort, and productivity impacts of mechanical ventilation systems often fall short of expectations (Fisk and Rosenfeld 1997; Fisk 1998). In comparisons of negative health symptoms of office workers in a limited number of naturally and mechanically ventilated systems, in both the European and North American context, the naturally ventilated buildings reported lower symptom prevalence in comparison to the mechanically ventilated and, especially, air conditioned buildings (Mendell et al. 1996). Beyond quantitative evaluations of health, comfort, and productivity advantages that natural ventilation systems may offer, it is important to recognize that many if not most building occupants may simply prefer natural ventilation systems qualitatively. Largely for these reasons alone, architects have accepted natural ventilation as one of several objectives of high quality sustainable design. Much anecdotal evidence supports these scientific findings, yet the fundamental reasons for them are not self-evident. Additionally, the indoor air quality of any space regardless of the type of ventilation system will depend largely on the type and strength of indoor contaminant sources and the quality of the outdoor air provided by the ventilation system.

2.2 Natural Ventilation Design Issues

Through the review of natural ventilation system design, development of tools, and performance of design examples, numerous natural ventilation design issues were identified. The design of natural ventilation systems logically involves the selection and specification of system components and building form *(system configuration*) for anticipated environmental conditions *(design conditions)* given a clear definition of ventilation objectives and associated performance criteria *(design requirements*). The often-overloaded word *design* must also be understood to be the process used to achieve these ends (Axley et al. 2002a). Thus, this section on design issues is organized around these aspects of design including a section on the design process, considering design methods and tools, and a section on design conditions and requirements.

2.2.1 Design Process

Technical systems are invariably configured by selecting and specifying the system's:

1. *General Configuration* – The selection of the general configuration of the ventilation system and, importantly, building form that will serve it.

2. *System Topology* – The selection of type and connectivity of system components needed.

3. *Component Sizes* – The selection of component sizes and related details to achieve specific natural ventilation objective(s) for anticipated environmental conditions.

4. *Control and Operational Strategies* – The selection of control and operational strategies to achieve specific natural ventilation objective(s) for anticipated environmental conditions.

In North America, the design process is commonly organized into five distinct phases:

1. *Predesign Programming and Analysis* – The definition of the building design program or brief that establishes design requirements and analytical investigations (e.g., climate and site analyses) needed to define design conditions.

2. *Conceptual or Preliminary Design* – The development of the general configuration and topology of the building system – often done with little quantitative analysis using intuition, precedents, general guidelines, and rules of thumb.

3. *Design Development* – The development of system component sizes and details and system control and operational strategies.

4. *Design Performance Evaluation* – Quantitative evaluation of the technical performance of the proposed system relative to the design requirements for given design conditions.

5. *Construction and Commissioning of the Proposed System.*

Consequently, a systematic and complete design method must provide empirical, analytic or algorithmic techniques to achieve the appropriate objective at each distinct phase of design. Three techniques – *climate suitability analysis*, *the loop equation design method,* and *detailed design performance analysis* – when applied in the order given, can largely achieve these ends.

2.2.1.1 Climate Suitability Analysis

The *climate suitability analysis* technique, described in section 2.1.1, was developed to evaluate the potential of a given location for direct ventilative cooling and complimentary nighttime ventilative cooling (i.e., of a building's thermal mass). As such, it is a useful predesign analytical technique. It also establishes preliminary estimates of design ventilation rates needed for preliminary design calculations (i.e., given knowledge of the likely internal gains in a building and local climatic conditions). Specifically, with it a designer may estimate the ventilation rate needed to offset internal gains when direct ventilation can be effective and the internal gains that may be offset by nighttime ventilation when direct ventilation will not work. The method may be applied to ventilative cooling achieved by natural, mechanical, or combined means. These preliminary estimates may then be used to compute estimates of ventilation system components sizes, using the loop equation design method described below, after the building designer selects an appropriate system configuration and topology (e.g., using examples of other building precedents or general design guidelines (Axley 2001, Emmerich et al. 2001, Irving and Uys 1997, Martin and Fitzsimmons 2000)). It is recommended that the climate suitability method be automated either as a stand-alone tool or as a pre-design component of LoopDA.

2.2.1.2 Loop Equation Design Method

Axley (2001) describes the Loop Equation Design Method that is proposed for the Design Development stage of the overall design process of a natural ventilation system in detail. The *Loop Equation Design Method* consists of the following eight steps:

1. Lay out the geometry and multi-zone topology of the building and identify the natural ventilation flow loops.
2. Identify an ambient pressure node and additional pressure nodes at entries and exits of each flow component along the loops.
3. Establish design conditions: wind pressure coefficients for envelope flow components, ambient temperature, wind speed and direction, and interior temperatures; evaluate ambient and interior air densities.
4. Establish design requirements: the required ventilation rates for occupied zones; apply continuity to determine the objective design airflow rates required for each natural ventilation flow component.
5. Form the forward loop equations for each loop established in step 1 above by systematically accounting for all pressure changes while traversing the loop.
6. Determine the minimum feasible sizes for each of the flow components by evaluating asymptotic limits of the loop equation for the design conditions.
7. Develop and apply a sufficient number of technical or non-technical design rules or constraints to transform the under-determined design problem defined by each loop equation into a determined problem.
8. Develop an appropriate operational strategy to accommodate the regulation of the natural ventilation system for variations in design conditions (e.g., with wind and without wind conditions).

NIST developed the LoopDA program (Dols and Emmerich 2003) as a means to perform these eight steps. While LoopDA does not fully automate all eight steps, it greatly simplifies and provides a means to manage the entire process. The initial version of LoopDA was developed with the main goal of demonstrating the method. This goal was satisfied as demonstrated through the application of LoopDA to real design projects (Taylor Engineering 2003). The strengths of LoopDA identified in this first demonstration included the value of using a fundamental approach to designing natural ventilation systems, the uniqueness of its inverse or "design" oriented method, the visual presentation provided to designers and architects by its interface, and its appropriate matching of the level-of-detail to the output validity/uncertainty yields a short time to value for the user.

Based on the design projects and feedback from other early users of LoopDA (AEC 2003), the tool itself could be improved upon to enhance its general usability and its applicability to a wider range of design and analysis scenarios as presented in the following list.

> *Integrate the capability to calculate design airflow rates.* Currently, LoopDA requires direct input of the design airflow rate required for each pressure loop. This is typically based upon either thermal load and/or air quality requirements. LoopDA could provide a simple means to determine these design airflows based on user inputs such as design indoor and outdoor temperature, occupancy level, lighting load, solar loads and thermal mass. LoopDA could

also provide a simple means to calculate airflow required to maintain steady state contaminant levels for various source types. Tables of ventilation requirements based on standard levels could also be integrated into the tool.

Couple the ability to simulate heat transfer and airflow within the analysis engine of LoopDA. This coupled analysis need only specifically address the class of problems associated with natural and hybrid ventilation systems and not attempt to be an all-encompassing tool for the analysis of all classes of building energy systems. Implementing combined airflow and heat transfer analysis would also provide a means to assess the performance of a design under varying conditions based upon weather data specific to the region of interest and to develop operation and control strategies.

Increase the set of inverse airflow components, i.e., those that can be used in implementing the sizing method. This set of components could be increased to provide a more complete set of airflow opening types including a self-regulating vent and possibly a fan type for hybrid system design. Airflow components could also be provided in forms that are more familiar to designers as opposed to generic mathematical representations (e.g., by type and size such as trickle ventilators, self-regulating vents, stack terminals etc.). This would also assist in applying design constraints during the sizing process.

Improve the general usability of the program. Potential improvements include a comprehensive tutorial that addresses specific design cases, modified nomenclature to speak more directly to building designers as opposed to multizone modelers, incorporation of the loop-asymptote plotting within LoopDA, and generation of reports summarizing design conditions and system design to enhance the usefulness of LoopDA in the documentation of the design process.

Provide statistical analysis of driving stack & wind pressures. Within the fundamental loop theory the driving stack and wind pressures depend only on system geometry and topology – i.e., they are independent of component sizes. Thus it is possible and desirable to compute driving stack and wind pressure time histories for a given season before beginning the LoopDA sizing procedure so that site-specific pressure design conditions may be evaluated via statistical analysis of these time histories.

2.2.1.3 Design performance analysis

With preliminary sizes of system components estimated and operational strategies defined, the designer can proceed to design performance analysis – the phase of design development used to estimate global measures of system performance and to fine-tune system characteristics. For natural and hybrid ventilation systems, performance evaluation must not only account for the coupled thermal/airflow interactions that characterize natural driving forces but must do so dynamically over long-term simulation time periods. Two important types of design performance analysis tools include multizone coupled airflow-thermal analysis and computational fluid dynamics (CFD). As a complete discussion of both multizone coupled airflow-thermal analysis and CFD is well beyond the scope of this section, the presentation here will be limited to a discussion of the type of results that may be produced using these types of analysis.

The research program CONTAM97R, presently under development, is a general-purpose multizone analysis program capable of coupled airflow-thermal simulation (Walton, 1998). In addition, this program has been designed to enable modeling of system control and non-trace air contaminant dispersal – useful for evaporative cooling schemes. Unfortunately, in its present state CONTAM97R has not been developed as a usable tool for the design community. However, as a demonstration, CONTAM97R was applied to the analysis of a reasonably well-documented naturally ventilated building – the Tax Office building of Enschede, The Netherlands (Axley 2001, and Axley et al. 2002). Comparisons of measured and predicted performance of this building in its native climate were presented as a means to provide a first validation exercise of CONTAM97R and to calibrate the building models used for subsequent analytical studies. A moderately detailed 11-zone model of the building was then used to design and analyze night ventilation cooling systems for the building in two hot-arid North American locations – Fresno and Los Angeles, California. Following a trial and error procedure using an overheated degree hour (ODH) performance metric, discussed below, component sizes were adjusted to achieve the night cooling objective.

The details of this demonstration need not be repeated here. Suffice it to say that a macroscopic tool like that provided by CONTAM97R provides essential spatial and temporal details that can guide design refinement relating to both whole-building and inter-room air distribution and thermal performance. In some cases, greater intra-room detail on airflows and temperatures may be required. In these cases, performance evaluation could proceed to detailed CFD studies of individual rooms. However, such CFD simulations are unlikely to replace multizone analysis as a whole building modeling technique in the foreseeable future.

2.2.2 Design Conditions and Requirements

Design conditions include the anticipated environmental conditions under which the natural ventilation system will need to operate. Two important aspects of the design conditions for natural ventilation systems include the weather and the ambient air quality. This section focuses on issues related to ambient air quality as those issues related to weather have already been discussed in Section 2.1.1 Climate Suitability. This section also discusses the primary related design requirements, or performance criteria, for natural ventilation system design including providing adequate air quality control and thermal comfort.

2.2.2.1 *Ambient Air Quality*

One important issue in determining the potential for natural ventilation systems in California and elsewhere is the impact of ambient air quality. While poor ambient air quality affects both mechanical and natural ventilated buildings, there are two reasons for greater concern with natural ventilation. First, as discussed in the review section, typical natural ventilation systems do not incorporate filtration. Although the filtration in mechanical ventilation systems does not remove all contaminants from the outdoor air, it generally includes some form of particle filtration. Second, in order to perform ventilative cooling, natural ventilation systems may introduce far greater quantities of outdoor air into the building.

Ideally, one would develop a metric to express the suitability of the outdoor air quality in a given location as has been presented and demonstrated by NIST for climate suitability. Unfortunately, the issue is not nearly so straightforward due to knowledge gaps such as the lack of specific health-based, contaminant concentration limits for indoor air and less standardized ambient air quality data compared with weather data. However, ASHRAE Standard 62-2001 (ASHRAE 2001) requires that the outdoor air used for ventilation in buildings meet the National Primary Ambient-Air Quality Standards set by the U.S. EPA (EPA1987) which sets concentration limits for sulfur dioxide, particles (referred to as PM 10), carbon monoxide, ozone, nitrogen dioxide, and lead. Additionally, California has established somewhat more restrictive ambient air quality limits than the national standards for some of these contaminants (http://www.arb.ca.gov).

Standard 62 allows several alternatives for determining whether the local ambient air quality meets the prescribed limits including monitoring data of the U.S. EPA or appropriate state or local environmental protection authorities. If outdoor air contaminant levels exceed the limits, Standard 62 recommends that the outdoor air to be treated to control the offending contaminants. As discussed earlier, natural ventilation systems typically do not include air filtration, however, the air cleaning equipment typically included in mechanical ventilation systems is unlikely to significantly impact the concentrations of ambient air pollutants other than coarse particles (i.e., larger than about 3 μm).

An earlier review of ambient air quality data indicates that much of California fails to meet the national standards for one or more contaminant (Emmerich et al. 2001). However, since ambient air quality problems may vary by season, time-of-day, and locality, natural ventilation strategies may still be considered acceptable at all times in some areas and part of the time in other areas by complementing the natural systems with innovative hybrid systems. Additionally, California has undertaken many emission control measures for the last three decades and, as a result, significant improvements have been made in ambient air quality. Continued improvement would lessen the concern about ambient air quality for natural ventilation systems. Also, it is important to note that the areas in California with better ambient air quality include much of the coastal area, which was shown to have high climate suitability for natural ventilation as discussed above.

Perhaps less obvious is the possibility that an area with a seasonal ambient air quality problem may be able to take advantage of some type of hybrid HVAC system that reduces outdoor air intake and/or treats outdoor air during the problem seasons. Even if ambient concentrations of some pollutants exceed recommended limits, the indoor levels may be acceptable due to deposition or other removal mechanisms. A multizone IAQ model such as CONTAMW could be used to predict indoor pollutant concentrations resulting from various scenarios of different ventilation rates, ambient concentrations, and indoor generation or removal processes.

2.2.2.2 Air Quality Control

As discussed earlier, natural ventilation may serve one of three primary objectives – air quality control, direct cooling, or indirect cooling via night cooling of building thermal mass. Performance criteria for air quality control are well established. They may be defined prescriptively in terms of minimum ventilation rates (e.g., ASHRAE Standard 62's *Ventilation Rate Procedure*) or by "restricting the concentration of all known contaminants of concern to some specified acceptable levels" (e.g., ASHRAE Standard 62's *Indoor Air Quality Procedure*) (ASHRAE 2001). Designing for a minimum ventilation rate (e.g., for offices ASHRAE Standard 62-2001 stipulates a minimum ventilation rate of 10 L/s-person) proves to be analytically straightforward yet "provides only an indirect solution to the control of air contaminants". Designing to restrict air contaminant concentrations is, on the other hand, far more difficult. Consequently, the prescriptive control of minimum ventilation rates is most often the approach taken in the design of natural and mechanical ventilation systems.

Since natural ventilation systems rely on natural driving forces instead of mechanical fans and air-conditioning to control comfort and IAQ in buildings, they may not reliably control comfort and IAQ under all ambient conditions. Proper design, maintenance, and operation are critical to attaining acceptable performance from natural ventilation systems. Alternatively, one could control minimum ventilation rates using air quality sensors – CO_2 demand controlled ventilation (Emmerich and Persily 2001) represents one common approach used in mechanical ventilation systems – but, again, this has proven to be difficult to achieve in natural ventilation

In addition, natural ventilation could have a negative impact on the moisture load in non-residential buildings in humid climates. Since most of the moisture load for many non-residential buildings is brought into a building through ventilation, increasing ventilation and eliminating or reducing air-conditioning can increase this moisture load.

2.2.2.3 Thermal comfort

Thermal comfort criteria for natural ventilation systems are not yet well established, although a number of approaches and even standards have been proposed. Fundamentally, a natural ventilation system intended for cooling a commercial building must provide thermal comfort but the growing evidence that individuals are more likely to adapt to seasonal variations when given the opportunity demands new approaches to the evaluation of thermal comfort (Axley 2001). Adaptation not only links the range of acceptable temperatures to changes in the outdoor air temperature (Brager and de Gear 2000) but to air velocities experienced directly by individuals (Olesen 2000) and the 'adaptive opportunity' provided by occupant control of lighting, shading, and airflow in buildings (Irving and Uys 1997).

Well-designed user-controlled natural and hybrid ventilation systems – especially when combined with user-controlled low-energy shading and lighting systems – offer the 'adaptive opportunity' that may well justify higher indoor air temperatures without compromising comfort. The Brager "adaptive standard for naturally ventilated buildings" establishes an indoor air control temperature comfort zone for office activities (i.e., less than 1.2 met) that varies from the range of 17 ºC to 22 ºC when outdoor air temperatures are 5 ºC or lower up to a range of 26 ºC to 31 ºC when outdoor air temperatures reach 34 ºC or higher (Brager and de Gear 2000). Beyond these adaptive impacts on comfort, increased air velocities are known to offset higher temperatures when these air velocities are personally controlled. While this additional advantage has yet to be codified into a standard (Olesen 2000), Arens and Miura (1998) reports comfort may be realized at air temperatures of 31 ºC with air velocities of 1 m/s to 1.2 m/s for moderate relative humidities supporting Brager's upper limit on the comfort zone for naturally ventilated buildings. Aynsley (1999) goes farther and claims the upper limit of the comfort zone may be increased by up to 3.7 ºC (above 30 ºC) for every meter per second of air velocity up to 2.0 m/s in hot humid environments.

When cooling by natural means, the upper limit of the thermal comfort zone may be exceeded from time to time due to the stochastic uncertainty of the natural driving forces. This inevitable reality must be accepted, within limits, if cooling by natural ventilation is to be pursued. Thus, beyond a well-defined and appropriate description of thermal comfort one must also establish limiting criteria for overheating. Irving and Uys (1997) reviews a number of proposed standards for assessing and limiting the degree of overheating. The BRE Environmental Design Manual places limits on the mean and standard deviation of summer and indoor air temperatures of 23 ºC ± 2 ºC for 'formal offices' and 25 ºC ± 2 ºC for 'informal offices'. In the Netherlands, dry resultant temperatures are not to exceed 25 ºC for more than 5 % of working hours and 28 ºC for more than 1 % of working hours. These and similar absolute approaches do not, however, quantify the degree of overheating. To remedy this shortcoming the 1994 ISO 7730 utilizes a weighted sum of penalty factors for temperatures greater than or equal to 25 ºC with larger penalty factors assigned to the higher temperatures (i.e., a penalty factor of 1.0 for 25 ºC to 4.2 for 30 ºC) (ISO 1994). This approach seems arbitrary and does not directly account for adaptive behavior.

Other standards have been proposed based on an accumulation of hourly temperature *exceedances* – i.e., the difference between actual or predicted indoor air temperature and a comfort upper limit when the indoor air temperature exceeds that limit – to produce an integrated *degree-hour* estimate of overheating. Of these, that used in Zurich Switzerland comes closest to accounting for adaptive behavior in that it employs an upper limit to thermal comfort that varies with outdoor air temperature. In Zurich, the limit on the integrated temperature exceedance is set at 30 degree-hours for a successful natural ventilation system design (Irving and Uys 1997).

Axley (2001) proposed assessing overheating using a variation of the Zurich method by accumulating the number of temperature exceedance degree hours (i.e., relative to the adapted Brager comfort standard discussed above) to evaluate the overheating degree hours (ODH) that is either observed or predicted for a given building design (see Figure 3). The upper limit to the Brager comfort zone may be defined as:

$$T_{upper} = \begin{cases} 22\,^{\circ}\mathrm{C} \;\; for \; \left(T_o \leq 5\,^{\circ}\mathrm{C}\right) \\ (9/28)T_o + 20.4\,^{\circ}\mathrm{C} \;\; for \; \left(5\,^{\circ}\mathrm{C} < T_o < 33\,^{\circ}\mathrm{C}\right) \\ 31\,^{\circ}\mathrm{C} \;\; for \; \left(T_o \geq 33\,^{\circ}\mathrm{C}\right) \end{cases}$$

With this limit in hand, the ODH may then be defined as the integrated sum of the temperature exceedances for the cooling season as:

$$ODH = \sum_{cooling\ season} \max\left\{\left(T_c - T_{upper}\right), 0\right\}\Delta t$$

where, Δt is the time increment for the record of indoor dry resultant temperatures T_c (e.g., 1 h when using hourly weather records for predictive assessments).

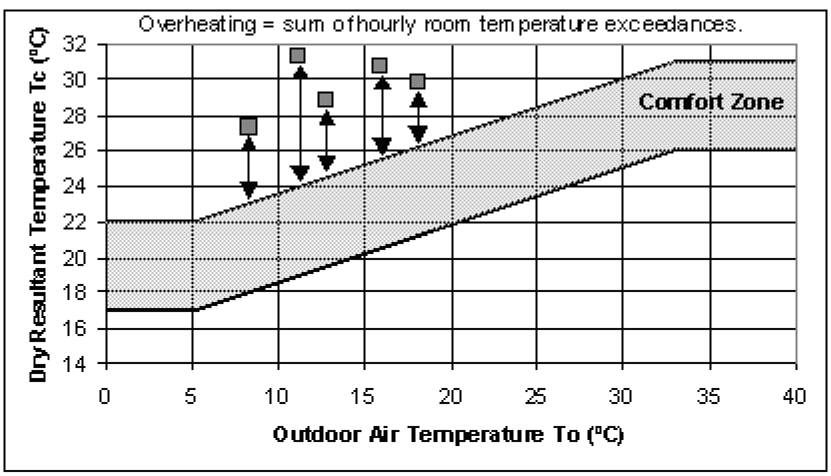

Figure 3 Adaptive thermal comfort zone based on Brager's proposed standard utilizing CIBSE's indoor dry resultant temperature

3. Potential Revisions to ASHRAE Standard 62 and California Title 24

An additional goal of the NIST research effort was to develop some suggested revisions to ASHRAE Standard 62 and California's Energy Efficiency Standards (Title 24) as they relate to natural ventilation. This section discusses the current requirements in both documents and suggests some potential revisions.

3.1 Current Requirements

Natural ventilation has long been recognized by ventilation standards and building codes, though never in terms of specifying engineering-based design methods such as those developed by NIST under the current project. This section discusses the current standard and regulatory context relevant to natural ventilation, specifically ASHRAE Standard 62 (ASHRAE 2001) and the California Energy Efficiency Standards, often referred to as Title 24 (CEC 2001).

ASHRAE Standard 62-2001 currently allows natural ventilation of buildings via Section 5.1, which permits the "use of natural ventilation systems … in lieu of or in conjunction with mechanical ventilation systems." This section then lists a number of requirements that such systems must comply with though it contains an exception for "engineered natural ventilation systems when approved by the authority having jurisdiction," but does not define what might constitute such an engineered system. The requirements for natural ventilation that are contained in the section include the following:

- Naturally ventilated spaces shall be permanently open to and within 8 m (25 ft) of operable wall or roof openings to the outdoors.
- The openable area of these openings shall be a minimum of 4 % of the net occupiable floor area.
- The means to open required operable openings shall be readily accessible to building occupants whenever the space is occupied.

Title 24 discusses natural ventilation under Section 121 Requirements for Ventilation. The requirements are very similar to those in ASHRAE Standard 62, allowing for the use of either natural or mechanical ventilation. The only differences are that the openings must be within 6 m (20 ft) of the opening instead of 8 m (25 ft) and that the openings must be greater than 5 % of the floor area instead of 4 %.

The current versions of ASHRAE Standard 62-1999, California's Title 24 Energy Efficiency Standards and most building codes allow the use of natural ventilation. All of the requirements are in terms of accessible openings that are sized based on 4 % to 5 % of the floor area of the ventilated space. None of these documents consider climatic conditions or ambient air quality in their requirements, though ASHRAE Standard 62 does require an assessment of outdoor air quality. While engineering-based approaches are likely to result in more reliable designs, none of the standards require their use. At the same time, they do not disallow them.

3.2 Potential revisions

Revisions to the material on natural ventilation in both ASHRAE Standard 62 and Title 24 merit consideration. The primary issues are the adequacy of the "traditional" requirements for opening area as a fraction of floor area, requirements for "engineered systems," and the recognition of hybrid or mixed-mode ventilation systems that employ both natural and mechanical ventilation. The issue with the traditional requirements for natural ventilation has to do with their adequacy in providing appropriate amounts of outdoor air to all spaces under the broad range of outdoor weather conditions. There is little doubt that under mild outdoor air temperatures and low wind speeds, the specified opening sizes are unlikely to result in adequate ventilation rates relative to the specific numerical requirements for mechanical ventilation systems. While these floor-area based requirements have a long history in building codes, that does not mean they are technically correct, and many view them as a "loophole" in the standard. In effect, one can comply with Standard 62 by providing such openings within the control of the building occupants, even if they are never opened. On the other hand, if one employs mechanical ventilation, then they are required to provide specific ventilation rates in cfm or L/s per person, presumably whenever the building is occupied.

Based on these concerns about the natural ventilation "loophole," some have suggested "beefing up" the engineered systems exception in Standard 62, which could also be added to Title 24. In effect, these suggestions would address the vagueness of the term engineered system by speaking to the provision of adequate levels of outdoor air over the range of weather conditions for the design climate. Two potential approaches were developed during committee discussions to replace the current exception, as follows:

Option #1

Exception: An engineered natural ventilation system need not meet the requirements of 5.1.1 and 5.1.2 providing the system is based on principles of pressure-driven airflows in buildings and considers weather data for the building site. The engineering approach on which the system design is based shall be documented, along with the outdoor air ventilation rates under a range of weather conditions including mild outdoor temperature and calm wind conditions.

Option #2

Exception: An engineered natural ventilation system need not meet the requirements of 5.1.1 and 5.1.2 providing the system design is documented as follows:

- The engineering approach on which the system design (e.g. calculation method used to determine outdoor air ventilation rates as a function of weather condition, airflow analysis software employed in the design)
- Outdoor air ventilation rates determined as part of design process at mean monthly outdoor air temperature and wind speed, and at a wind speed for <u>1 m/s (2 mph)</u> and an outdoor air temperature of <u>15 °C (60 °F)</u>
- Demonstration that the system will provide the outdoor air requirements in Table 2 for at least <u>80</u> % of the hours of the year

The second option is obviously more detailed, and the specific weather conditions are underlined to indicate that they are simply potential values that could be used or replaced as determined by committee deliberations. It also could encourage the use of engineering-based design methods, including software such as LoopDA, via the second bullet.

Finally, the issue of addressing the use of hybrid or mixed-mode systems would require both Standard 62 and Title 24 to take a slightly different approach to that in the current versions of the document that are essentially based on an "either-or" approach. An alternative approach would be to simply provide the ventilation rate requirements as is done in Table 2 of Standard 62, and in the analogous section of Title 24, and then allow the use of mechanical, natural or combination system to meet them. The designer could then be required to document how their design approach would provide the ventilation rates. This documentation would be relatively straightforward for mechanical systems, as it could employ current design methods. For natural and hybrid systems, the options noted above could be used.

4. ADDITIONAL RECOMMENDATIONS

Besides the potential changes to codes and standards discussed in Section 3.2, this project has identified numerous recommendations that will further the goal of realizing the potential of natural ventilation in commercial buildings in California. These recommendations are discussed in two categories: research and technology transfer.

4.1 Research

Hybrid systems: As discussed in this report, the future of both natural and mechanical ventilation appears to lie in the emerging field of hybrid ventilation system design. Thus, future work is needed to address hybrid approaches in more detail. NIST is currently pursuing research in the application of hybrid ventilation systems through an ongoing simulation study for the Air-Conditioning and Refrigeration Technology Institute, which is aimed at comparing the performance of natural, mechanical, and hybrid ventilation systems in an office building set in U.S. climates.

Improved research/analysis tools: There is a need for a wide variety of proven computational tools for both design and research tools. Tools aimed primarily at researchers or for advanced performance analysis are discussed here while tools aimed primarily at design engineers or architects are discussed in section 4.2. There are numerous analysis capabilities useful to both researchers and advanced design engineers that are either lacking in current analysis tools or are unproven in application to natural ventilation system analysis. Chief among these are coupled thermal-airflow analysis, non-trace 'contaminant' analysis, and dynamic control of ventilation systems, each of which is discussed further below.

As discussed above, the need to couple heat transfer with multi-zone airflow modeling capabilities has been recognized in the literature and was highlighted during the design examples study. Thermal and airflow interactions are characteristic of natural ventilation airflow systems. Indeed, leading researchers in the field state emphatically and unequivocally that the practical design of natural and hybrid ventilation systems demands analysis of these coupled interactions. Efforts are underway on several fronts to perform this integration at NIST and elsewhere. However, numerical problems of stability, convergence, and solution multiplicity have yet to be completely resolved when performing this integration. A research version of the CONTAM family of programs has been recently used in modeling studies of a five story building in a number of U.S. climates. Initial comparisons of measured and predicted building performance are not only encouraging but clearly demonstrate the critical need for such complete modeling (Axley 2001 and Axley et al. 2002). NIST has also recently completed a project utilizing a coupled thermal/airflow simulation tools created through a combination of CONTAMW with the building energy analysis subroutine of the TRNSYS simulation program (McDowell et al. 2003).

Multi-zone analysis tools typically provide airflow and contaminant dispersal analysis (i.e., for air quality evaluation). Without exception, available contaminant dispersal analysis tools assume air contaminants exist at trace levels and, thus, do not influence the buoyancy of the airflow. Recent interest in so-called "evaporative down-draught chimneys" wherein a water spray is used to evaporatively cool and induce downward airflow in inlet chimneys and thereby force warmer air out of exhaust chimneys has forced the need for non-trace "contaminant" analysis (i.e., treating water vapor content as a "contaminant"). This particular natural ventilation cooling strategy is based on ancient Middle Eastern precedents and, in its technically more developed versions, appears to be a very attractive strategy for hot arid urban environments. The newest version of CONTAM (Dols and Walton 2002) includes non-trace analysis capabilities based on fundamental theory but these capabilities have yet to be studied systematically for purposes of validation and practical application to analysis of natural ventilation systems.

While considerable and important progress in passive strategies of controlling natural ventilation systems has been achieved in the past decade, it is now clear that passive control devices – most notably self-regulating vents – must be complemented by active control of system settings. Furthermore, the improved performance demonstrated by very recent hybrid ventilation systems that necessarily demand active control places an even greater need on the development of modeling tools to simulate active control of ventilation systems. Again, both the latest version of CONTAM and the research version of CONTAM include control analysis capabilities but these capabilities have yet to be studied systematically for purposes of validation and practical application to natural and hybrid ventilation system analysis.

Performance monitoring – Detailed performance monitoring of notable demonstration buildings with natural and hybrid ventilation in the U.S. (see 4.2 for more) will provide invaluable information on several fronts. Such quality data can serve as proof of design performance, provide feedback to improve future designs, validate simulation models, etc.

4.2 Technology Transfer

In addition to further research and perhaps more important, the realization of the energy savings potential of natural and hybrid ventilation in California and the rest of the U.S. will depend on various technology transfer efforts including the development of better design tools, demonstration projects, and symposia/workshops.

Design tools: As with the research/analysis tools discussed above, new and/or improved design tools are needed for the practicing design engineer/architect. Besides audience, a key difference is that these design tools require primarily software development rather than real research. One significant interest for NIST is to develop a second version of LoopDA (Dols and Emmerich 2003). The initial version of the loop-sizing tool was developed with the main goal of demonstrating the method. This goal was satisfied, however, the tool itself could be improved upon to enhance its usability to the design community and its applicability to a wider range of design and analysis scenarios in a number of ways including capability to determine design airflow rates, combining airflow and heat transfer, inclusion of additional airflow components, and user interface improvements. These issues are discussed in more detail in section 2.2.1.

Another need is a tool to perform the climate suitability analysis that has been proposed as an initial phase in designing natural ventilation systems. This could be developed as either a stand-alone tool or as a pre-design component of LoopDA.

Demonstrations: In Europe, innovation in the design of natural and hybrid ventilation systems is driven largely through the example of innovative built projects. Indeed, the lively competition to achieve extreme low-energy building designs economically among building designers appears, presently, to be a more important impetus for innovation than even the aggressive European research activities. Axley (2001) lists dozens of significant and interesting examples of such buildings along with references to some design and performance information for these buildings. Practically all the buildings listed not only combine mechanical assistance of one sort or another with natural ventilation systems but these systems are complemented by comprehensive daylighting, solar control systems, state-of-the-art artificial lighting systems, and low-energy equipment to minimize internal gains and energy-efficient mechanical systems and often energy storage systems to further reduce energy consumption and associated greenhouse gas emissions.

While these and other buildings may serve as examples from afar, the spread of natural and hybrid ventilation systems to commercial buildings in the U.S. will depend on demonstration buildings readily available for visiting and mimicking. The federal building currently under construction in San Francisco can serve as one important demonstration building. The Philip Merrill Environmental

Center of the Chesapeake Bay Foundation (www.cbf.org/merrillcenter) is another example. It is a modern office building featuring operable windows intended for use in conjunction with a conventional mechanical system via an energy management system that can alert occupants when outdoor conditions are favorable for opening windows. More such examples are needed – particularly in the category of smaller nonresidential buildings where the greater potential for widespread application exists.

Symposia/workshops: Innovation in natural and hybrid ventilation systems is being driven in Europe largely by aggressive and forward looking professional design firms. In a very real sense, their efforts are outpacing research in the field and, as a result, are setting research agendas. Recognizing the need to communicate new ideas within the profession these European design professionals – often identified as "building environmental engineers" – have organized a number of symposia. Perhaps foremost among these symposia is the Intelligent Building Design symposia held annually for the last six decades. Similar symposia could be mounted in the U.S. This would most reasonably be done early-on by selecting the most innovative presentations from the European symposia and inviting the presenters to participate in a regional or national symposium in the U.S. To take full advantage of the specialized knowledge these practitioners currently have, design workshops should be organized to complement such a symposium.

5. REFERENCES

AEC. 2003. Memorandum from Z. Rogers to W.S. Dols, Architectural Energy Corporation.

Arens,E., X.,T., Miura K. "A Study of Occupant Cooling by Personally Controlled Air Movement. 1998, Energy and Buildings, No. 27, pp. 45-59.

Arnold, D. (2000). “Thermal Storage Case Study: Combined Building Mass and Cooling Pond.” ASHRAE Transactions Vol. 106(Part 1).

ASHRAE. 2001. Standard 62-2001, Ventilation for Acceptable Indoor Air Quality. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA.

Axley, J.W. *Application of Natural Ventilation for U.S. Commercial Buildings*. GCR-01-820 NISTIR 6781, National Institute of Standards and Technology. 2001.

Axley, J.W. and S.J. Emmerich. 2002. “A Method to Assess the Suitability of a Climate for Natural Ventilation of Commercial Buildings”, Proceedings of Indoor Air 2002.

Axley, J.W., Emmerich, S., Dols, S., and G. Walton. 2002a. “An Approach to the Design of Natural and Hybrid Ventilation Systems for Cooling Buildings”, Proceedings of Indoor Air 2002.

Axley, J.W., Emmerich, S., and G. Walton. 2002b. “Modeling the Performance of a Naturally Ventilated Commercial Building with a Multizone Coupled Thermal/Airflow Simulation Tool”, ASHRAE Transactions Vol 108 Pt 2.

Aynsley, R. *Unresolved Issues in Natural Ventilation for Thermal Comfort*. in *HybVent Forum '99*. 1999. Sydney, Australia.

Berry, J. (2000). "Super-Efficient Mechanical Ventilation" Indoor and Built Environment, Vol. 9 (No.2) pp. 87-96.

Brager, G.S. and R. de Gear (2000). “A Standard for Natural Ventilation” ASHRAE Journal October 2000.

Braham, G. D. (2000). “Comparative Performance of U.K. Fabric Energy Storage Systems.”

California Energy Commission. 2001. AB970 Energy Efficiency Standards for Residential and Nonresidential Buildings, P400-01-024.

Dols, W.S. and S.J. Emmerich. *LoopDA – Natural Ventilation Design and Analysis Software.* National Institute of Standards and Technology. 2003.

Dols, W.S. and G.N. Walton. *CONTAMW 2.0 User Manual*. National Institute of Standards and Technology. 2002.

Emmerich, S.J., Dols, W.S., and J.W. Axley. 2001. Natural Ventilation Review and Plan for Design and Analysis Tools. NISTIR 6781, National Institute of Standards and Technology.

Emmerich, S.J. and A.K. Persily. 2001. State-of-the-Art Review of CO_2 Demand Controlled Ventilation Technology and Application. NISTIR 6729, National Institute of Standards and Technology.

EPA (1987). National Primary and Secondary Ambient Air Quality Standards, Code of Federal Regulations, Title 40 Part 50 (40 CFR50), as amended July 1, 1987. U.S. E.P.A.

Fisk, W. J. and A. H. Rosenfeld (1997). “Estimates of Improved Productivity and Health from Better Indoor Environments.” Indoor Air 1997(7): pp. 158-172.

Fisk, W. J. (1998). Improved Productivity and Health from Better Indoor Environments: Estimates of Potential National Benefits. Berkeley, CA, Lawrence Berkeley Laboratory.

Haves, P., Carilho da Graca, G., and P. Linden. 2003. "Use of Simulation in the Design of a Large Naturally Ventilated Commercial Office Building." Proceedings of Building Simulation 2003.

Heiselberg, P. (1999). "The Hybrid Ventilation Process - Theoretical and Experimental Work." Air Infiltration Review Vol. 21(No. 1): pp. 1-4.

Heiselberg, P. (2000). Design Principles for Natural and Hybrid Ventilation. Healthy Building 2000, Espoo, Finland, SIT Indoor Air Information Oy, Helsinki, Finland.

Irving, S. and E. Uys, CIBSE Applications Manual: Natural Ventilation in Non-domestic Buildings. 1997, CIBSE: London.

ISO, *ISO 7730:1994 - Moderate thermal environments -- Determination of the PMV and PPD indices and specification of the conditions for thermal comfort*. 1994, International Organization for Standardization: Geneva.

Marion, W. and K. Urban. *User's Manual for TMY2s*. National Renewable Energy Laboratory, 1995.

Martin, A. and J. Fitzsimmons. 2000. Guidance Note GN 7/2000: Making Natural Ventilation Systems Work. Bracknell, Bershire, UK, BSRIA - The Building Services Research and Information Association.

McDowell, T.P., Thornton, J.W., Emmerich, S., and G. Walton. 2003. "Integration of Airflow and Energy Simulation Using CONTAM and TRNSYS", ASHRAE Transactions Vol 109 Pt 2.

Mendell, M. J., W. J. Fisk, et al. (1996). "Elevated Symptom Prevalence Associated with Ventilation Type in Office Buildings." Epidemiology November 1996, Vol.7: 6: pp. 583-589.

Olesen, B.W., *Guidelines for Comfort.* ASHRAE Journal, 2000. August: p. 41-46.

Taylor Engineering. (2003). *LoopDA Testing and Evaluation Report*. Alameda, CA.