

**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<sup>2</sup> to 80 W/m<sup>2</sup>.

**Table 1 California locations used for initial climate suitability evaluation.**

Coastal	Inland
<i>San Diego</i>	<i>Daggett</i>
<i>Long Beach</i>	<i>Bakersfield</i>
<i>Los Angeles</i>	<i>Fresno</i>
<i>Santa Maria</i>	<i>Sacramento</i>
<i>San Francisco</i>	
<i>Arcata</i>	

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.,  $3.4 \text{ h}^{-1} \pm 8.7 \text{ h}^{-1}$ ). 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  $0 \text{ h}^{-1}$  to  $5 \text{ h}^{-1}$  and  $5 \text{ h}^{-1}$  to  $10 \text{ h}^{-1}$  ranges respectively – both quite reasonable using commonly available natural ventilation strategies. Results in medium and darker gray ( $10 \text{ h}^{-1}$  to  $15 \text{ h}^{-1}$  and above  $15 \text{ h}^{-1}$ ) will be more difficult to achieve using available natural ventilation strategies.

For example, the Bakersfield results show that an average ventilation rate of  $3.4 \text{ h}^{-1} \pm 8.7 \text{ h}^{-1}$  may be expected to provide direct ventilative cooling when the internal gain is  $10 \text{ W/m}^2$  ( $3.2 \text{ Btu/ft}^2\cdot\text{h}$ ). 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  $3.2 \text{ W/m}^2\cdot\text{h}^{-1} \pm 2.6 \text{ W/m}^2\cdot\text{h}^{-1}$

( $1.0 \text{ Btu/ft}^2\text{h}\cdot\text{h}^{-1} \pm 0.81 \text{ Btu/ft}^2\text{h}\cdot\text{h}^{-1}$ ). Thus to offset a specific internal gain of  $10 \text{ W/m}^2$  ( $3.2 \text{ Btu/ft}^2\cdot\text{h}$ ), the average nighttime ventilation rate would have to be  $10 \div 3.2 \geq 3.1 \text{ h}^{-1}$ . (Here, the  $\geq$  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 <sup>1</sup>
	10 W/m <sup>2</sup>	20 W/m <sup>2</sup>	40 W/m <sup>2</sup>	80 W/m <sup>2</sup>	
<b>Arcata</b>					
Vent. Rate or Cooling Potential	1.1 ±0.4 h <sup>-1</sup>	1.7 ±0.8 h <sup>-1</sup>	3.3 ±1.7 h <sup>-1</sup>	6.7 ±3.4 h <sup>-1</sup>	10.5 ±1.5 W/m <sup>2</sup> •h <sup>-1</sup>
% Effective <sup>2</sup>	74 %	100 %	100 %	100 %	100 % (2 d)
% Heating	26 %	0 %	0 %	0 %	
<b>Long Beach</b>					
Vent. Rate or Cooling Potential	2.3 ±5.6 h <sup>-1</sup>	4.4 ±11.1 h <sup>-1</sup>	8.7 ±22.1 h <sup>-1</sup>	17.4 ±44.3 h <sup>-1</sup>	6.2 ±2.7 W/m <sup>2</sup> •h <sup>-1</sup>
% Effective <sup>2</sup>	88 %	91 %	91 %	91 %	92 % (95 d)
% Heating	3 %	0 %	0 %	0 %	
<b>Los Angeles</b>					
Vent. Rate or Cooling Potential	1.7 ±1.9 h <sup>-1</sup>	3.3 ±3.8 h <sup>-1</sup>	6.6 ±7.7 h <sup>-1</sup>	13.2 ±15.4 h <sup>-1</sup>	6.6 ±2.2 W/m <sup>2</sup> •h <sup>-1</sup>
% Effective <sup>2</sup>	96 %	97 %	97 %	97 %	100 % (55 d)
% Heating	1 %	0 %	0 %	0 %	
<b>San Diego</b>					
Vent. Rate or Cooling Potential	1.8 ±3.3 h <sup>-1</sup>	3.6 ±6. h <sup>-1</sup>	7.2 ±13.0 h <sup>-1</sup>	14.5 ±26.1 h <sup>-1</sup>	3.6 ±2.3 W/m <sup>2</sup> •h <sup>-1</sup>
% Effective <sup>2</sup>	91 %	92 %	92 %	92 %	90 % (52 d)
% Heating	1 %	0 %	0 %	0 %	
<b>San Francisco</b>					
Vent. Rate or Cooling Potential	1.3 ±1.3 h <sup>-1</sup>	2.2 ±2.6 h <sup>-1</sup>	4.5 ±5.1 h <sup>-1</sup>	8.9 ±10.3 h <sup>-1</sup>	8.6 ±2.6 W/m <sup>2</sup> •h <sup>-1</sup>
% Effective <sup>2</sup>	90 %	99 %	99 %	99 %	100 % (12 d)
% Heating	10 %	0 %	0 %	0 %	
<b>Santa Maria</b>					
Vent. Rate or Cooling Potential	1.4 ±1.8 h <sup>-1</sup>	2.4 ±3.4 h <sup>-1</sup>	4.9 ±6.9 h <sup>-1</sup>	9.7 ±13.8 h <sup>-1</sup>	11.2 ±2.8 W/m <sup>2</sup> •h <sup>-1</sup>
% Effective <sup>2</sup>	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 <sup>1</sup>
	10 W/m <sup>2</sup>	20 W/m <sup>2</sup>	40 W/m <sup>2</sup>	80 W/m <sup>2</sup>	
<b>Bakersfield</b>					
Vent. Rate or Cooling Potential	3.4 ±8.7 h <sup>-1</sup>	5.7 ±16.1 h <sup>-1</sup>	11.5 ±32.2 h <sup>-1</sup>	22.9 ±64.3 h <sup>-1</sup>	3.2 ±2.6 W/m <sup>2</sup> •h <sup>-1</sup>
% Effective <sup>2</sup>	64 %	77 %	77 %	77 %	94 % (159 d)
% Heating	12 %	0 %	0 %	0 %	
<b>Daggett</b>					
Vent. Rate or Cooling Potential	3.4 ±8.9 h <sup>-1</sup>	5.8 ±16.5 h <sup>-1</sup>	11.6 ±32.9 h <sup>-1</sup>	23.2 ±65.8 h <sup>-1</sup>	3.7 ±2.9 W/m <sup>2</sup> •h <sup>-1</sup>
% Effective <sup>2</sup>	60 %	71 %	71 %	71 %	86 % (169 d)
% Heating	11 %	0 %	0 %	0 %	
<b>Fresno</b>					
Vent. Rate or Cooling Potential	2.9 ±7.2 h <sup>-1</sup>	4.6 ±12.8 h <sup>-1</sup>	9.2 ±25.6 h <sup>-1</sup>	18.3 ±51.1 h <sup>-1</sup>	4.3 ±2.8 W/m <sup>2</sup> •h <sup>-1</sup>
% Effective <sup>2</sup>	63 %	81 %	81 %	81 %	100 % (161 d)
% Heating	18 %	0 %	0 %	0 %	
<b>Sacramento</b>					
Vent. Rate or Cooling Potential	2.3 ±6.5 h <sup>-1</sup>	3.8 ±11.6 h <sup>-1</sup>	7.6 ±23.2 h <sup>-1</sup>	15.1 ±46.4 h <sup>-1</sup>	7.0 ±2.2 W/m <sup>2</sup> •h <sup>-1</sup>
% Effective <sup>2</sup>	69 %	88 %	88 %	88 %	100 % (142 d)
% Heating	19 %	0 %	0 %	0 %	

<sup>1</sup> Night cooling for days when direct cooling is not effective.

<sup>2</sup> For direct cooling % = hours effective ÷ 8760 h; for night cooling % = days effective ÷ days needed.

white = 0 h<sup>-1</sup> to 5 h<sup>-1</sup>

light gray = 5 h<sup>-1</sup> to 10 h<sup>-1</sup>

medium gray = 10 h<sup>-1</sup> to 15 h<sup>-1</sup>

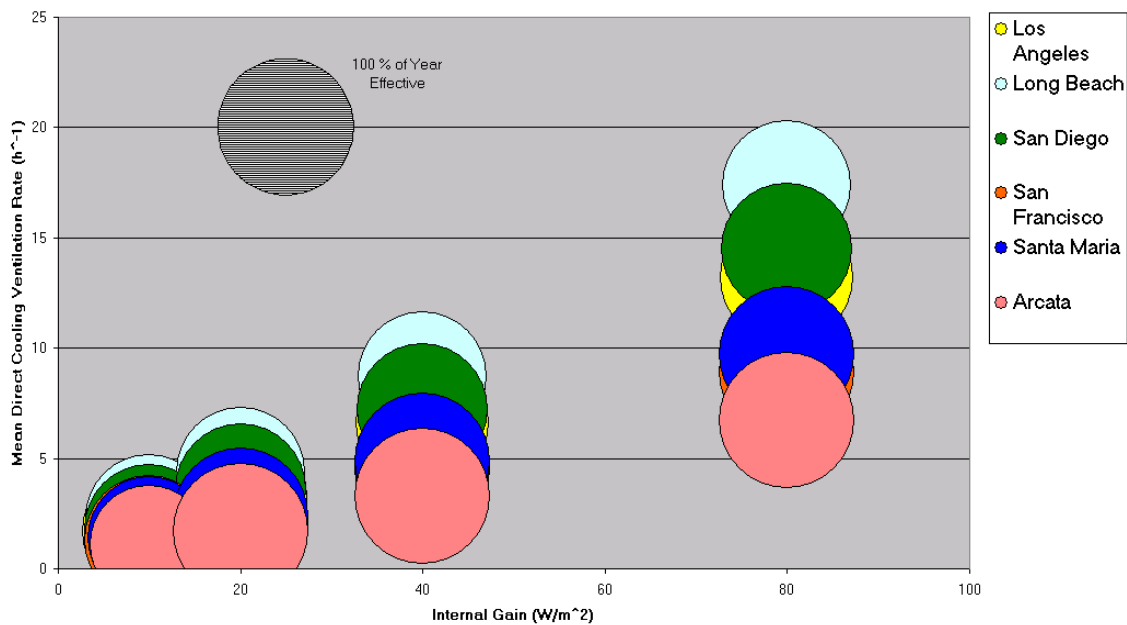
dark gray > 15 h<sup>-1</sup>

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.

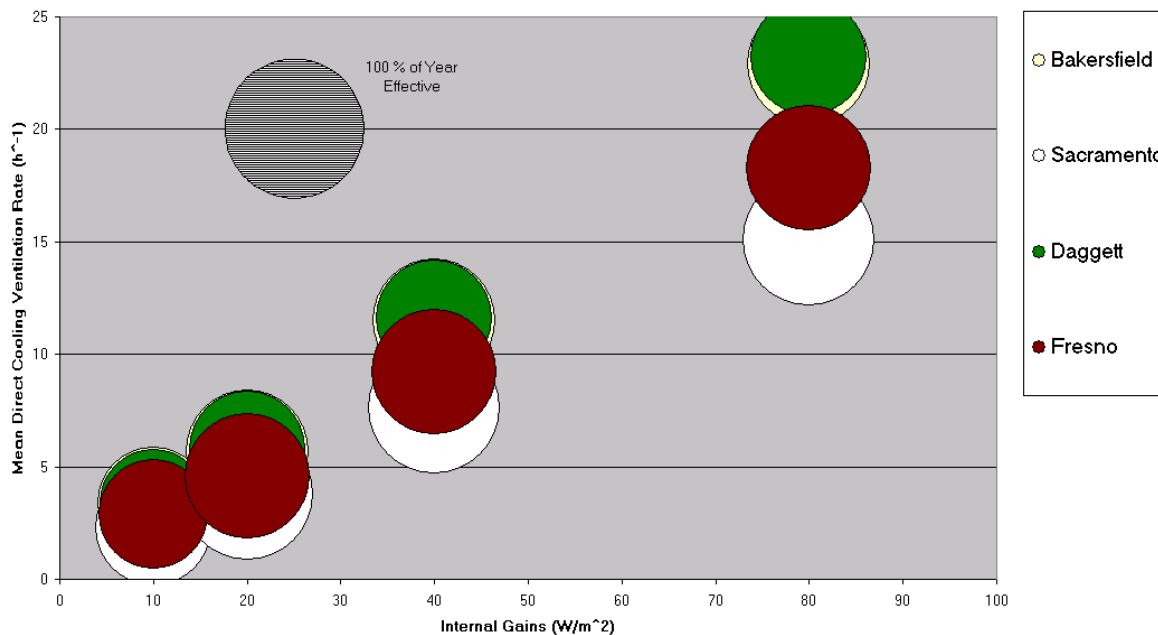
As might be expected, Table 2 and Figure 1 show that natural ventilation strategies could have a very significant impact in California. Specifically, the coastal climates of California are very well suited to natural ventilation with respect to climatic considerations. For most of these locations, the 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  $5 \text{ h}^{-1}$  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) than 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. *Pre-design 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 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. 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  $\mu\text{m}$ ).

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<sub>2</sub> 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 °C to 22 °C when outdoor air temperatures are 5 °C or lower up to a range of 26 °C to 31 °C when outdoor air temperatures reach 34 °C 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 °C 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 °C (above 30 °C) 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 °C ± 2 °C for ‘formal offices’ and 25 °C ± 2 °C for ‘informal offices’. In the Netherlands, dry resultant temperatures are not to exceed 25 °C for more than 5 % of working hours and 28 °C 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 °C with larger penalty factors assigned to the higher temperatures (i.e., a penalty factor of 1.0 for 25 °C to 4.2 for 30 °C) (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).

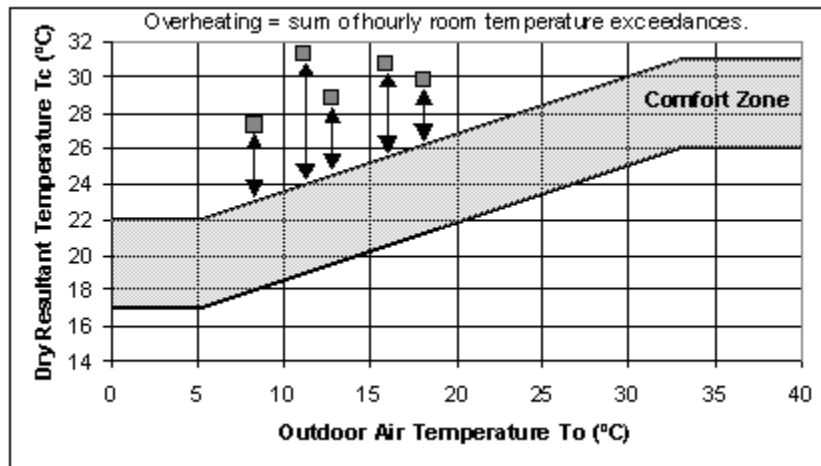
Axley (2001) proposed assessing overheating using a variation of the Zurich method by accumulating the number of temperature exceedance degree hours (i.e., relative to the adapted Brager comfort standard discussed above) to evaluate the overheating degree hours (ODH) that is either observed or predicted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

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

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

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

where,  $\Delta t$  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 1 m/s (2 mph) and an outdoor air temperature of 15 °C (60 °F)
- Demonstration that the system will provide the outdoor air requirements in Table 2 for at least 80 % 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](http://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.

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