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**Review of Literature Related to
Residential Ventilation
Requirements**

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Abstract

This paper reviews current ventilation codes and standards for residential buildings in Europe and North America. It also examines the literature related to these standards such as occupant surveys of attitudes and behavior related to ventilation, and research papers that form the technical basis of the ventilation requirements in the standards. The major findings from the literature are that ventilation is increasingly becoming recognized as an important component of a healthy dwelling, that the ventilation standards tend to cluster around common values for recommended ventilation rates, and that surveys of occupants showed that people generally think that ventilation is important, but that their understanding of the ventilation systems in their houses is low.

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INTRODUCTION

With an increasing public concern about mold and other indoor air quality concerns inside their homes, many jurisdictions and institutions are looking to adopt improved ventilation codes, standards and practices. The State of California, for example, is planning to update the 2008 version of its energy code, known as “Title 24” to address this issue.

Indoor air quality (IAQ) is a complex result of occupant activities, human responses, source emission, and contaminant removal. The key issues that one can set requirements for are usually ventilation and source control. To set those requirements often requires an understanding of the materials and processes typically found in houses and the operational strategies of its occupants.

The purpose of this report is to review the published literature on existing ventilation standards and related research in order to provide a foundation for the current efforts to update Title 24 Residential Building Energy Code.

BACKGROUND

Virtually every building code has requirements in it related to ventilation and indoor air quality, but an integrated approach to looking at residential indoor air quality is usually lacking. The nation’s first consensus standard on residential ventilation and indoor air quality was recently published by the American Society of Heating, Refrigerating and Air-conditioning Engineers (ANSI/ASHRAE Standard 62.2-2003). As the first such American National Standard it forms a strong starting point; other codes and standards can be compared to that.

CALIFORNIA PROGRAMMATIC BACKGROUND

The California Energy Commission (CEC) has as a funding priority a program of Research and Development (R&D) to advance the state of knowledge on residential ventilation in California. The Energy Commission will support this research through its Public Interest Energy Research (PIER) program. An important goal of this effort is to identify changes to existing residential energy efficiency standards (i.e., Title 24) that can be incorporated into the 2008 standards to maintain or to improve the indoor environment of new homes and to reduce the energy-related impacts of these homes.

To advance the state of knowledge in this field, the PIER program has established a three-part approach to the problem: 1) characterization of the indoor environments of homes built to current standards, 2) development of minimum requirements to achieve acceptable indoor air quality in future construction and 3) evaluation and development of technologies and associated descriptive algorithms for meeting minimum requirements.

These three elements act synergistically to provide the information the State needs to inform its efforts to modify Title 24. Each piece has been the subject of an independent scoping study (Walker and Sherman, 2003 and McKone and Sherman, 2003). This report provides a review of the literature necessary to achieve the following goals.

Characterization Project Goals: The broad goals of the characterization project are: 1) to determine if ventilation and indoor air quality, in a population of new, production-built, single-family, detached houses built to 2001 Title 24 energy efficiency standards, are acceptable based on available guidelines for comfort and health protection and 2) to describe the influence of selected key factors, including occupant behaviors, on ventilation rates and indoor air quality in these houses. The objective of this project is to answer a series of questions related to ventilation rates and indoor air

quality (IAQ) in production-built, new, single-family, detached California homes built to the 2001 Title 24 standards. These questions focus on the topics of ventilation, indoor air quality and occupant behavior.

Requirements Project Goals: The broad goals of the requirements project are to: 1) determine the state of the art in residential ventilation codes and guidelines and their applicability to California; 2) identify and resolve engineering-based issues necessary to define new minimum requirements; 3) determine how to extend engineering-based requirements with R&D to incorporate health protection; and 4) develop draft requirements suitable for inclusion in the 2008 version of Title 24. The objectives of the project are to focus on the technical barriers to improved residential ventilation standards and to resolve these barriers. We will closely coordinate work on this project with the characterization project to identify real-world issues and problems for ventilation and indoor air quality in new construction.

Technology Project Goals: The broad goals of the technology project are to: 1) determine the state of the art in residential ventilation methods and technologies and their application to California; 2) identify and develop suitable technologies that meet new minimum requirements and are not currently used in California; 3) develop models to evaluate the full performance of potential technology using the applicable criteria of energy, ventilation, demand, etc. and 4) work with the compliance industry to incorporate necessary algorithms into future Title 24 compliance tools.

REVIEW OF CURRENT CODES AND STANDARDS

In developing a new standard, code or practice it is important to review what others have done. In this section we look at the ever-changing list of such documents:

The European Union is in the process of bringing the standards of the various countries into alignment with a European Standard. The Union has issued two directives that relate to ventilation: the Construction Product Directive (CPD) issued in 1989, and the Energy Performance of Buildings Directive (EPBD) issued in 2002 (Santamouris, to be published). The area in which the CPD relates to ventilation is that it requires construction product standards that relate to hygiene, health and the environment (among others) to be aligned within the member countries. The EPBD mainly deals with the energy efficiency of buildings, but it does contain the following reference to ventilation: *“These [energy] requirements shall take account of general indoor climate conditions, in order to avoid possible negative effects such as inadequate ventilation,...”*. (CEC, 2003) The European Committee for Standardization (CEN) is the body responsible for most of the standards relating to ventilation. They currently have a standard, *prEN 14788: Ventilation for buildings – Design and dimensioning of residential ventilation systems*, which describes a calculation method for determining the ventilation air volume flow rate required for good health of the occupants based on pollutant production rates and certain indoor and outdoor air conditions. Due to the widely varying methods of specifying ventilation rates in the Regulations and Standards of each of the European member countries, the standard does not attempt to align these requirements, or even tabulate them. It states that *“The required ventilation air flow rates shall be obtained from National or Local Regulations and/or Standards in the country concerned.”* (CEN, 2003)

Table 1, excerpted from AIVC Technical Note 57: Residential Ventilation, gives a succinct summary of required whole building and room by room ventilation rates in Europe, the U.S. and Canada (Concannon, 2002). The ventilation must be supplied mechanically in some of the standards, but not in all. Several standards have been updated since the publishing of this paper, and these are shown in Table 2.

Country and Standard Reference	Whole Building Ventilation Rates	Living Room	Bedroom	Kitchen	Bathroom + WC	WC only
Belgium (NBNB62-003)	0.7-1.0 ach 20-30 m ³ /h/p		1.0 dm ³ /s/m ² floor area	50-75 m ³ /s	14 dm ³ /s	7 dm ³ /s
Canada (CSA F361-M1989, ASHRAE 62-1989)	>0.3 ach, 5 l/s/p			Exhaust 50 l/s (inter.) 30 l/s (cont.)	Exhaust 25 l/s (inter.) 15 l/s (cont.)	
Denmark (DS 418)		0.4-0.6 ach		0.7 ach	0.7 ach	
Finland (NBC-D2)		0.5 l/s/m ²	4.0 l/s/p 0.7 l/s/m ² floor area	Exhaust 20 l/s	Exhaust 15 l/s	
France (Arrete 24.03.82)				20-135 m ³ /h	15-30 m ³ /h	15-30 m ³ /h
Germany (Din 18017, Din 1946, VDI 2088)		Min. 60-120 m ³ /h Max. 60-180 m ³ /h		Min. 40 m ³ /h Max. 60 m ³ /h	Min. 40 m ³ /h Max. 60 m ³ /h	Min. 20 m ³ /h Max. 30 m ³ /h
Italy (MD 05.07.75)	0.35-0.5 ach	15 m ³ /h/p		1.0 ach	1.0-2.0 ach	
Netherlands (NEN 1087)		1.0 dm ³ /s/m ² floor area	1.0 dm ³ /s/m ² floor area	21 dm ³ /s	14 dm ³ /s	7 dm ³ /s
New Zealand (ASHRAE 62-1989)	Openable Window to 5% of floor area in each room.				25 l/s per room (inter.) 10 l/s per room (cont.)	
Norway (NBC ch47-1987)		Supply: Openable window or inlet bigger than 100cm ² in external wall.	Supply: Openable window or inlet bigger than 100cm ² in external wall.	Mech. Extract 60m ³ /h or by natural extract at least 150cm ² duct above roof	Mech. Extract 60m ³ /h or by natural extract at least 150cm ² duct above roof	Mech. Extract 40m ³ /h or by natural extract at least 100cm ² duct above roof
Sweden (BFS 18ch4.1)	Supply: min. 0.35 l/s/m ² floor area	Supply: 0.35 l/s/m ² floor area	Supply: 4.0 l/s/p	Extract: 10 l/s per room	Extract: 10-30 l/s	Extract: 10 l/s
Switzerland (SIA 384/2, SIA 382/1)			80-120 m ³ /h		30-60 m ³ /h	
UK (BS 5720-1979, BS5925-1991, Building Regs. Approved Doc. F, CIBSE Guides A & B)	Rec. 12-18 l/s/p, Min. 8-12 l/s/p	Vent openings with at least 1/20 th floor area & vent openings with total area not less than 4000mm ²	Vent openings with at least 1/20 th floor area & vent openings with total area not less than 4000mm ²	Mech. Supply 60 l/s (inter.) or 30 l/s cooker hood & natural vent. Openings with total area not less than 134000mm ²	15 l/s (inter.)	Openings not less than 1/20 th floor area or 3ach intermittent with overrun.
USA (ASHRAE 62-1989)	0.35 ach but no less than 7.5 l/s/p			50 l/s (inter.) or 12 l/s (cont.) or openable windows	25 l/s per room (inter.) or 10 l/s per room (cont.) or openable windows	

Table 1: Ventilation Standards in Dwellings, Concannon (2002)

Country and Standard Reference	Whole Building Ventilation Rates	Living Room	Bedroom	Kitchen	Bathroom + WC	WC only
USA (ASHRAE 62.2-2003)	0.05 * (total floor area) + 3.5 l/s/p			50 l/s (inter.) or 5 ach (cont.) or openable windows	25 l/s per room (inter.) or 10 l/s per room (cont.) or openable windows	
Finland (NBC-D2, 2003)		0.5 l/s/m ²	6.0 l/s/p or 0.35 l/s/m ² floor area	Exhaust 8 l/s (cont.) 25 l/s (boost)	Exhaust 10 l/s (cont.) 15 l/s (boost)	Exhaust 7 l/s (cont.) 10 l/s (boost)

Table 2: Standards that have been updated since the publishing of AIVC TN 57 in 2002

LISTING OF RELEVANT CODES AND STANDARDS

In the sections below we list the most important ventilation codes, standards and practices for dwellings.

AMERICAN NATIONAL STANDARDS

- ASHRAE 62.2-2004: Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings
- ASHRAE 62.1-2004: Ventilation for Acceptable Indoor Air Quality
- ASHRAE 90.2-2003: Energy Code for New Low Rise Residential Buildings
- Uniform Building Code (1994)
- Uniform Mechanical Code (2000) *This code only deals with combustion makeup air and evaporative cooling. It references the Uniform Building Code.*

MODEL CODES

- International Residential Code (2003)
- International Energy Conservation Code (2003)
- CABO MEC (1996) *This code references ASHRAE 62-1989. Many state codes reference CABO MEC.*

STATE AND FEDERAL REGULATIONS

- CA Title 24
- Other States
 - Washington State Ventilation and Indoor Air Quality Code (2000)
 - Minnesota Rules Chapter 7672 : Energy Code (2000) *Alternative compliance by Minnesota Rules Chapter 7670: Energy Code (1994).*
 - Florida Building Code. *This code references ASHRAE 62-1989*
 - Vermont Residential Building Energy Standard (2003)
- Department of Housing and Urban Development: Directive Number 3280.103 *This standard applies only to manufactured homes.*

INTERNATIONAL CODES AND STANDARDS

- Sweden: BFS 1998:38: Hygiene, health and the environment
- UK: The Building Regulations 1991 Document F: F1 Means of Ventilation

- France: Arrêté du 24.03.82 relatif à l'aération des logements (relating to the ventilation of residences)
- Denmark: DS 418:2002 Calculation of Heat Loss from Buildings
- Finland: D2 Finnish Code of Building Regulations, Indoor Atmosphere and Ventilation of Buildings, Regulations and Guidelines, 2003
- Australia: AS 1668.2 – 2002: The use of Ventilation and Air Conditioning in Buildings
- Canada: Residential Mechanical Ventilation Systems CAN/CSA–F326 or alternatively the Canadian National Building Code, Section 9 – Ventilation.

LABELS, GUIDELINES AND OTHER VOLUNTARY PRACTICES

- Energy Protection Agency Indoor Air Quality Standard (Proposed)
- American Lung Association Health House
- NFPA 54 National Fuel Gas Code. *This code addresses only back-drafting.*

COMPARISON OF KEY REQUIREMENTS

Each of these documents is different, but many of them address similar aspects of the problem and consider similar types of requirements. In this section we will compare these documents across some of these requirements:

COMPLIANCE DEMONSTRATION

Many of the standards are prescriptive in nature, meaning that they prescribe that a certain airflow be provided by a mechanical ventilation system. CA Title 24, and the Florida Building Code, and are set up in this way. Testing is not required to verify that the installed system actually provides the airflow required. Some standards are mainly prescriptive with some performance component such as The American Lung Association (ALA) Health House, where the only performance component relates to the airflow of the heating and/or cooling system. In other standards, such as ASHRAE Standard 62.2, the compliance mechanism is performance, with a prescriptive alternative. The airflow required by this standard refers to the delivered airflow, as verified by a test of the installed system. As an alternative to this performance approach, the airflow rating of the fan may be used if the ductwork is also in compliance with the standard. The Canadian standard is framed in the same way, with the National Building Code requiring that ventilation systems conform to CAN/CSA F326 "Residential Mechanical Ventilation Systems", which is performance in nature, or comply with the prescriptive requirements laid out in the National Building Code. The Washington State Ventilation and Indoor Air Quality Code also has dual paths for compliance: performance or prescriptive. The Minnesota State Code and the Energy Protection Agency Indoor Air Quality (EPA IAQ) Standard require that ventilation comply with the ASHRAE Standard 62.2.

WHOLE-HOUSE VENTILATION RATES

Whole house ventilation is needed to dilute pollutants (such as VOC's) originating from the building components and to remove pollutants (such as moisture and CO₂) that are created due to human activity. Whole house ventilation regulations are prescribed on a per square foot basis, a per person basis, or a combination of the two. CA Title 24 and the MN energy code are examples of codes that use a per square foot basis. ASHRAE Standard 62.2 and the ALA Health House use a combination of square footage and number of people. The Washington State Ventilation and Indoor Air Quality Code uses either a standard based on the number of people, or 0.35 air changes per

hour (ACH), whichever is bigger. The Canadian Building Code and the Swedish Building Code specify ventilation rates that must be provided to each room. For the Canadian code the rate is 10 cfm (5 l/s) for each room except the master bedroom and basement which require 20 cfm (10 l/s). The Swedish code requires 8 cfm per square foot (0.35 l/s per square meter) of floor area in occupied rooms. In addition it requires 8.5 cfm (4 l/s) per bed space of supply capacity.

Whole house ventilation can be achieved with a continuously operating fan, or by fans operating intermittently at a higher flow rate. Most of the standards are written with the continuous fan operation requirement, and then have some allowance for how that requirement can be met with an intermittently operating fan. ASHRAE Standard 62.2, for example, requires a continuous ventilation rate of 1 cfm per 100 sq ft of building area plus 15 cfm per person. An intermittent fan can meet this requirement if it operates at least one hour out of every twelve, provides the same volume of outdoor air as the continuous scenario plus an additional volume of air to make up for a loss in ventilation effectiveness by the intermittent fan. The current version of CA Title 24 requires 0.047 cfm/square foot of continuous mechanical ventilation if the building has a low leakage design (SLA < 3), and it requires the house to be continuously pressurized to 5 Pa if the building is “unusually tight” (SLA < 1.5). There is no clause about how this standard can be fulfilled by an intermittently operating fan.

LOCAL EXHAUST RATES

Most of the codes require 100 cfm capacity for kitchen fans, and 50 cfm capacity for bathroom fans. These codes alternatively allow the kitchen and bathroom venting to be performed by a lower capacity, continuously operating fan. The value is usually 20 cfm continuous for bathrooms, and 20-30 cfm (or 5 ACH in the case of ASHRAE Standard 62.2) for kitchens.

INFILTRATION

Ventilation may be provided by infiltration in only two of the standards: ASHRAE Standard 62.2 where a blower door test of the building shell allows the builder to provide some of the ventilation air through infiltration, and CA Title 24 where the mechanical ventilation requirement only holds if the building has a Specific Leakage Area (SLA) less than 3.0.

OPERABLE WINDOWS

The ventilation standards generally do not have specific requirements about operable windows since windows in habitable spaces are addressed in the building codes. The International Residential Code (IRC), for instance, states that all habitable rooms must have a minimum openable area to the outdoors of not less than 4 percent of the floor area. Alternatively, ventilation may be provided by a ventilation system that provides 0.35 air changes per hour to the space, or a whole-house ventilation system that supplies 15 cfm per occupant as determined by the number of bedrooms plus one. Bathrooms are required to have at least 1.5 square feet of openable area to the outside, or a ventilation fan with 50 cfm ventilation capacity or 20 cfm of continuous ventilation. The IRC allows habitable spaces to have no window (operable or not) at all if the space is properly ventilated, and lighted with artificial light.

Two of the ventilation standards do have regulations regarding operable windows: ASHRAE Standard 62.2, which states that each habitable room, and each toilet or utility room must have an operable window and the Swedish standard where every habitable space must have an operable window. These standards do not account for new houses that are designed with an interior bath

(meaning all of the bathroom walls are interior partition walls) where this requirement cannot be met.

AIR DISTRIBUTION AND DUCT LEAKAGE

In an ideal ventilation system, fresh air would be provided to every room in the house, and polluted air would be drawn from the rooms in which it is produced. It is especially important that fresh air be provided to the bedrooms since they are occupied longer than any other area of the house. When a mechanical ventilation system is required, virtually every code specifies that a certain volume of air be exhausted from the bathroom and kitchen, however, few codes have requirements for distributing fresh air throughout the dwelling. The exceptions to this are Canada, where fresh air must be distributed throughout the dwelling¹, and Sweden, where 8 cfm per square foot (0.35 l/s per square meter) of floor area must be provided continuously in occupied rooms. The rate may be reduced when the room is unoccupied. Some codes have the requirement of air inlets in every room (ASHRAE 62.2, Washington State, Minnesota), but there must be a negative pressure in the room in order to bring air in through the inlet. So whether the inlets actually provide distributed fresh air depends on equal depressurization of the building by the exhaust system. Similarly, exhaust only systems (without air inlets) rely on an even distribution of leaks throughout the house to deliver fresh air to every room. In a house with a leaky envelope (as we have in the United States) this condition is usually met, but in tight houses such as those in Canada and in Europe, this condition is often not met, hence the need for air distribution requirements.

Duct leakage can be a dominant source of ventilation in houses with tight building envelopes and leaky ductwork. Unfortunately, ventilation air obtained in this manner has a high energy penalty, and likely contains contaminants from the attic or basement where the ducts run. No standards were found that allowed duct leakage as a method to supply indoor ventilation air. However, some of the standards have limits for duct leakage as an IAQ source control issue. Return duct leaks can pull contaminated air into the house from interstitial spaces where the ducts are located, and supply leaks can depressurize the house, pulling unfiltered outside air in through the building envelope. ASHRAE Standard 62.2 limits HVAC return duct leakage to 6% of total fan flow in ducts that run inside garage spaces. The Swedish Building code states that ducts should be tight enough that there is no bypass leakage from supply to return. The EPA IAQ standard says that no ducts are allowed in the garage. Maximum allowable HVAC duct leakage is 3 cfm/100sq ft at 25 pascals. No building cavity ducts (meaning the building cavity is the duct) are allowed. Transfer grilles are required to each room if there is no return in that room except for bathrooms, kitchens and laundry rooms. The ALA Health house limits duct leakage to 0.03 cfm/ sq. ft. of conditioned floor area for ducts outside conditioned space, and to 0.07 cfm/ sq. ft. for ducts inside conditioned space. It also does not allow air handlers or HVAC ducts in the garage or in an unconditioned attic.

COMBUSTION EQUIPMENT

All combustion equipment including furnaces, boilers, hot water heaters, wood stoves, fireplaces, gas cooking appliances, etc. need a certain volume of air as an ingredient for combustion, and to carry the combustion products away from the house occupants. This volume of air is called “combustion air”. Safety problems can arise when air does not follow the intended path through the appliance and out the flue. Downdrafting is when outdoor air enters the house by downward movement through the flue when no combustion is occurring. Backdrafting occurs when the

¹ Residential Mechanical Ventilation Systems, CAN/CSA-F326, requires 10 cfm (5 l/s) for each room except the master bedroom and basement which require 20 cfm (10 l/s), however the National Building Code only specifies that the fresh air be distributed. Compliance in Canada can be met by satisfying either of these codes.

combustion appliance is unable to reverse this flow when firing, causing spillage, or entry of combustion gasses into the indoor air. (Wray, 2001)

Some combustion appliances are sealed combustion, meaning that the air supply and exhaust for the appliance does not mix with the air in the house. In these types of appliances spillage cannot occur. Other appliances have a dedicated air inlet to supply combustion air, but are not completely sealed from the house air, and still others take the combustion air directly from the air in the house. Spillage may occur in these appliances if the pressure conditions cause backdrafting. Mechanical ventilation can cause depressurization of the zone around the combustion appliance increasing the likelihood of backdrafting, therefore ventilation standards sometimes include safeguards to prevent this from happening. Many of the newer furnaces are induced draft, meaning that they have a fan to aid the combustion gasses in exiting the flue. Backdrafting is less likely in this type of furnace.

The NFPA 54: National Fuel Gas Code regulates the installation of gas appliances. It states that “A venting system shall be designed and constructed so as to develop a positive flow adequate to remove flue or vent gases to the outside atmosphere.” The standard addresses IAQ by requiring that combustion product exhausts must be located at least 6-12 (depending on size of combustion equipment) inches away from air intakes. Makeup air is stipulated by 50 ft³ per 1000 Btu/hour (4.8 m³/kW) minimum required room volume for a combustion appliance that uses room air for combustion in a building where infiltration is unknown. If the infiltration rate is known, another method can be used if the air exchange rate is less than 0.60 ach, and must be used if the exchange rate is less than 0.40 ach. This second method stipulates 21 ft³ (or 15 ft³ if the appliance has fan assisted draft) divided by the air change rate per 1000 Btu/hour. If the makeup-air volume requirement cannot be met then a permanent opening must be installed between the combustion appliance space and the outside.

Many codes require makeup air to reduce negative pressure caused by exhaust fans or testing for spillage. The ALA Health house simply states to “reduce the depressurization of the building.” ASHRAE Standard 62.2 states that the net flow, at full capacity, of the largest two exhaust fans cannot be greater than 15 cfm/100 ft² of occupiable space. If this condition is not met, compensating airflow must be provided, maximum flow reduced, or atmospherically vented combustion appliances inside the conditioned space must be tested for spillage. CA title 24 requires that glass doors and an air inlet be provide for each fireplace and each wood, pellet or gas stove. The Minnesota code limits "excessive depressurization" except when all appliances are sealed combustion and 3 biggest exhaust fans have a combined flow less than 425 cfm. There are 4 prescriptive paths or a performance test to show compliance. The Canadian code requires make up air for exhaust flow greater than 150 cfm if there is a chimney vented oil or gas appliance in the house. The EPA IAQ standard goes even farther to require a direct vent or power vented water heater. It also requires a direct vent furnace if the house is located in a climate with more than 4000 Heating Degree Days (HDD).

FILTRATION AND AIR CLEANING

Since the main purpose of ventilation is to provide clean air for people to breathe, filtration can be an important component of a ventilation system. ASHRAE Standard 62.2 requires a heating or cooling system to have at least a MERV 6 filter. The EPA IAQ standard requires MERV 8 filters, and no filter bypass is allowed. A neoprene gasket is required on one side of filter rack to bring the filter into contact with the rack. The ALA Health House requires at least a MERV 10 filter in the heating or cooling system. In Sweden, they require that the return air is filtered, and that there is no return air from bathrooms, kitchens, or other apartments. (The requirement of no return air from bathrooms and kitchens are standard in building codes, and are contained in the IRC.) It is also

required that the ducts be clean-able.

OTHER SOURCE CONTROL MEASURES

Clothes dryers are required to be vented to the outside in the IRC, in the Washington State code, and in the ALA Health House. Additionally, the Washington State code requires a pool or spa area to be vented. The EPA IAQ standard requires 100 cfm of continuous exhaust from the garage. ASHRAE Standard 62.2 limits HVAC return duct leakage to 6% of total fan flow in ducts that run inside garage spaces, and it requires that the walls and ceiling between the garage and the house be sealed before insulation is installed, and that doors be gasketed between the garage and living space.

OTHER OCCUPANTS ISSUES

The major occupant issue that is addressed in the ventilation standards is control of the system. A French survey of 10,000 households (Lemaire et al. 2000) found that occupants are more satisfied with ventilation systems that offer occupant control. ASHRAE Standard 62.2, The Minnesota Energy Code and the Canadian Building code all require that the occupant be given override (if not total) control of the ventilation system.

There was only one code that addressed an occupant comfort issue: Swedish code requires the velocity of air supplied to an occupied zone to be less than or equal to 0.15 m/s in heating mode and less than or equal to 0.25 m/s in cooling mode.

NOISE AND OTHER EQUIPMENT ISSUES

Several codes addressed the issue of fan noise. ASHRAE Standard 62.2 gives a maximum noise rating of 1 sone for continuous fans, and 3 sones for intermittent fans. The philosophy is that quiet, unobtrusive fans will get left on, while noisy ones will be turned off by the occupant. Fans with flow greater than 400 cfm are exempt from the noise requirements. This exemption allows noisy (and high flow) kitchen range hood fans to be installed. The Washington ventilation code limits fan noise for ventilation systems where the fan is within 4 feet of the grille at 1.5 sones. The ALA Health House also has the limit of 1.5 sones for fan noise. The Minnesota code has a maximum of 1 sone for surface mounted fans.

The EPA IAQ guideline requires a carbon monoxide alarm outside each sleeping area in homes with combustion appliances.

OUTDOOR AIR

Outdoor air is always a part of a ventilation system, whether it enters the house through dedicated inlets, supply fans, or through unintentional openings in the building shell. The standards that require dedicated air inlets are ASHRAE 62.2, Washington State, Minnesota, Canada and Sweden. Inlets must be 10' from known contamination such as exhausts vents, stack pipes and vehicle exhaust in ASHRAE 62.2, EPA IAQ, ALA Health House, and the IRC.

ENERGY AND DEMAND IMPACTS

Some of the ventilation standards have maximum energy requirements, and others leave the energy regulations to standards dedicated to energy use in buildings. The ventilation standards that

have specific requirements for energy usage are the ALA Health House that specifies a maximum of 0.5 watt per cfm for exhaust fans, and 1 watt per cfm for HRV's. Minnesota requires a maximum of 0.8 W per cfm for residential (constant air volume) systems.

California Title 24 is an energy standard so it dictates that when mechanical ventilation is installed, the power of the fans is and the extra infiltration load is added to the building energy usage for performance compliance.

CLIMATIC OR REGIONAL DIFFERENCES

The climates that are significantly different such that they receive special attention from a ventilation perspective are cold climates and warm-humid climates. Cold climates have the issue that ventilation air entering the building shell in the winter will be uncomfortable for the occupants unless it is tempered before it reaches them. Canada, Minnesota, and the EPA IAQ guideline have requirements for tempering incoming air. ASHRAE 62.2 has the requirement that mechanical supply systems exceeding 7.5 cfm/100 ft² shall not be used in severe cold climates, which include most of Canada, and the upper half of most US states that boarder Canada.

In warm-humid climates the concern is humidity which can damage building components, if forced into walls. ASHRAE 62.2 has the requirement that mechanical exhaust systems exceeding 7.5 cfm/100 ft² shall not be used in hot-humid climates, which include areas that boarder the Gulf of Mexico. The ALA Health house states that vinyl wallpaper may not be used in hot-humid climates due to the concern about mold and mildew growth when water condenses on the back of the vinyl. The EPA IAQ guideline contains three options for controlling humidity inside dwellings in warm-humid climates: controls that ensure humid outdoor air is not supplied to the interior, whole house dehumidification, or enthalpy exchange equipment.

OCCUPANT ACCEPTABILITY, CONTROL AND BEHAVIOR

The purpose of the codes, standards and guidelines we review are generally to provide a minimum amount of health, safety and comfort for the occupants. A part of that is subjective because it involves the perceived acceptability of the indoor environment to those occupants. This section reviews the literature related to ventilation and IAQ-related behaviors and attitudes of residential occupants.

Determining occupant behavior can sometimes be done through objective scientific measurements, but determining occupant acceptability usually requires the use of surveys, questionnaires, etc.

OCCUPANT SURVEYS

The Energy Commission, through the California Air Resources Board, is currently conducting an occupant survey in new California homes. The results of this survey are not yet available, but that survey is based on other surveys of a similar nature.

The surveys that have been done can be broadly divided into those having to do with occupant perception of the ventilation and IAQ of their residence, and the occupant behavior with respect to the ventilation of the residence. Occupant behavior has been extensively studied, by means of interviews and questionnaires and also by more quantitative means such as activity diaries, direct

observation, and sensors to monitor for specific behavior. The interviews and questionnaires in the behavior studies sometimes include questions related to perception of the ventilation and IAQ since the perception influences the behavior. All the studies having to do with people's perception of the ventilation in their homes also had a behavior component.

People generally believe that ventilation systems are beneficial. In Canada 60 homes were surveyed to determine the performance and people's perception of heat recovery ventilators (Hill, 1998). Most of the occupants thought the heat recovery ventilator was beneficial and understood the general purpose of the equipment. In the state of Washington 235 households were surveyed (Devine, 1999) to reveal attitudes about ventilations systems such as: "people are concerned about indoor air quality and believe fresh air is important for health." The reasons given for why occupants ventilate (Dubrul, 1988) are: to get fresh air into bedrooms and living rooms, to remove odor, to remove stale air and condensation, to 'air' the dwelling during residential activities, and to remove tobacco smoke. The reasons given for not ventilating are: to prevent draughts, to maintain a preferred temperature, to protect against cold and rain, to maintain privacy and safety, and to reduce external noise and pollution.

The understanding that people have of their ventilation systems is generally fairly low. In a Canadian study, the occupants' knowledge of how to operate and maintain the system was found to be very low (Hill, 1998). In the Washington study (Devine, 1999) one quarter of the people surveyed were not aware that their house had a mechanical ventilation system, perhaps because many of the mechanical ventilation systems were integrated with the forced air heating system. In another Canadian study of exhaust only ventilation systems, almost 10% of the people surveyed had no idea how they operated their ventilation system. Another 70% of those surveyed operated the system incorrectly (Fugler, 2004). A study of 43 Minnesota homes found that people need more information and guidance about the operation and maintenance of their ventilation systems (Sheltersource, 2002).

When considering satisfaction with system, 20% of respondents in a Washington study "considered noise, drafts and/or energy waste a problem with their system" (Devine, 1999.) In a study of 10,000 French households (Lemaire and Trotignon et al. 2000), only 9.2% of people with balanced ventilation systems found noise to be a problem, and 6.7% of people with single flow ventilation systems (exhaust or supply only) found noise a problem. This study also found that overall, 81% of the survey respondents were satisfied with their ventilation systems. Satisfaction increased with the age of the head of the household, household income, number of rooms in the dwelling, and surface area of dwelling. Higher satisfaction is also correlated with people who clean their vents, and with systems that allow occupant control. 22% of the survey respondents reported problems with their ventilation systems such as condensation from humidity, dampness on walls, persistent odors, ventilation noise, cold draughts, or dust/stains due to ventilation. Fewer problems were reported in owner occupied houses (about half the rate of problems reported in rental properties), and in dwellings where the ventilation system could be switched off. The number of problems reported was found to be inversely related to length of time since move in.

Occupant behavior has been widely studied as it relates to ventilation. AIVC Technical Note 53, Occupant Impact on Ventilation (Liddament 2001), offers a comprehensive review on occupant interaction with ventilation systems in residential and non-residential buildings.

Liddament examines:

- basic statistics on housing occupation and ventilation systems
- basic ventilation and indoor climate needs
- observed occupancy interaction with ventilation systems and controls
- occupant impact on the total ventilation/ air exchange rate

- occupant impact on energy consumption
- and lessons learnt and procedures for optimizing occupant interaction

His key findings were:

- Dwellings are often occupied 24 hours a day
- Ventilation is necessary to provide air for metabolism, dilute and remove pollutants, and provide combustion air for fossil fuel heating appliances.
- Pollutants that need to be vented include metabolic CO₂ and odor, moisture from bathing, cooking and clothes washing, combustion products from unvented gas cooking appliances, and tobacco products.
- Occupant behavior has a significant effect on ventilation, particularly in relation to window opening.
- Finally, he provides a set of occupant guidelines to provide good indoor air quality and comfort without excessive energy usage.

Windows have historically been a main source of ventilation in dwellings. 71% of households in California report door or window opening for longer than 1-2 minutes a day according to Phillips et al. (1990) and Wiley (1991). Less window opening was found during the winter (57%), and less was found in the non-costal regions (32%). The conclusion of this survey was that adequate supply of fresh air was not supplied to a substantial portion of homes, particularly during the colder seasons of the year, and in colder climates. It is important to note that when the temperature is cold outside, infiltrative ventilation is increased. This contributes to the decreased need for window opening when it is cold. (Kelly et al. 1993) In a New York state study of 141 households, 30% were found to open windows in the winter, and 78% opened them in the summer. The National Human Activity Pattern Survey 1992-94 provides data on window opening behavior in the United States. Tsang and Klepeis (1996) tabulate the data by many variables including gender, age, race, census region, season, asthma, angina and bronchitis/emphysema. In spring and summer 54% of respondents reported leaving windows open, as opposed to approximately 30% in fall and winter. IEA Annex 8 (Dubrul, 1988) summarized findings from numerous studies on window opening reported in Table 3.

Factor	Observed Trend
Occupancy density	Window opening increases with number of occupants present.
Occupant's age	The amount of window opening and ventilation reduces with the increasing age of the occupants.
Outdoor air temperature	Window opening decreases with decreasing outdoor air temperature, although a significant number are still opened at temperatures as low as -5 deg. C.
Sunshine	More windows tend to be open on the sunny side of buildings than on the opposite side.
Wind speed	Window opening decreases with increasing wind speed.
Day time opening	Windows are usually closed when the building is unoccupied during the day.
Night time opening	A significant number of windows are kept open in bedrooms at night, even in cold weather.
Weekend opening	Windows are open more frequently on weekends than during the rest of the week.

Thermostat setting	The higher a household sets its heating thermostat, the less often windows are opened.
Residential activities	Reasons given for window opening include vacuum cleaning, and airing of bed-clothes, cooking, odour and moisture problems.
Smoking	Windows are opened twice as frequently in smoking households than in non-smoking households.
Energy use	There is only a weak correlation between energy saving intentions and window opening. More window opening tends to take place in buildings in which heating energy is not separately metered to occupants.

Table 3: Factors Relating to Window Opening Behavior, IEA Annex 8, Dubrul (1988)

Another question of interest, which has been widely studied, is **“Do people use their ventilation systems?”** Buildings may have no intended ventilation system, or they may have one of three types of systems: passive systems, mechanical systems with unidirectional flow, or bidirectional mechanical systems. The French study (Lemaire and Trotignon, 2000) reported that 46% of dwellings have passive ventilation systems, meaning intentional air inlets and/or outlets but no fan. In the UK, a study (Oseland 1995) showed that 7-8% of passive stacks were blocked up compared to 13% of all vents (mechanical and natural) reported to be blocked in the French study. The fraction of blocked vents drops to 6-7% in dwellings built after 1982. This shows that most of the passive systems that are installed are in daily use.

Unidirectional mechanical systems consist of exhaust only systems or supply only systems. Exhaust only systems are much more common, and more appropriate in cold climates where cold dry air brought in through leaks in the building shell will not damage the building components, and will be tempered before it gets to the living space. Supply only systems are rarely used, but are appropriate when it is advantageous for the building shell to be pressurized, as in a moist climate where outdoor air must be dehumidified before entering the house, for the comfort of the occupant as well as for the health of the building. In Canada, Fugler (2004) found exhaust only ventilation (EOV) systems as the most common, installed in 76% of the houses. 30% of the EOV system owners never used the system and most of the other owners used the system only for bathroom ventilation, although a significant number of homeowners had window condensation or stuffiness in the house. In California, Phillips et al. (1990) and Wiley (1991) found that only a 3% of the statewide population used exhaust fans. Slightly higher percentages were found in the winter (5%) and in the San Francisco region (7%). In France, 17% of dwellings were found to have extract ventilation (Lemaire and Trotignon, 2000). Almost one quarter of those systems could not be turned off by the occupant, about half of the systems could be turned off, but were rarely or never turned off by the occupant, and another quarter of the systems were often or fairly often turned off.

Bidirectional flow or balanced mechanical ventilation systems are becoming more popular in France. Lemaire and Trotignon (2000) report that 9% of dwellings built since 1989 have this type of system as opposed to 1.5% in buildings built before 1948. Balanced systems are most common in cold countries such as Canada and Scandinavia, where heat recovery ventilators are used to temper the air coming into the house, and to recover the heat from the air leaving. In Canada, Hill (1998) reports that 17% of the houses surveyed had blocked their air intakes, much higher than the number of intakes blocked in the UK and in France, but this may have to do with the colder climate. More than half, 60%, of the houses surveyed had substandard ventilation due to poorly maintained systems. As in the EOV study in Canada, 55% of the occupants who's systems required running the furnace fan at the same time to distribute the air, were not aware of this.

OTHER OCCUPANT STUDIES

The current literature provides clear indications of links between human health and ventilation and of the need for addressing these links through guidelines and standards. In research from office buildings as reviewed by Seppanen et al. (1999, 2002) relatively strong and consistent associations have been found between ventilation and health. In their review of 105 papers dealing with ventilation and health in non-industrial indoor environments, Wargocki et al. (2002) report that ventilation requirements in many existing guidelines and standards may be too low to protect occupants of offices, schools, and homes from health problems and may not be optimal for human productivity. Wargocki et al. (2002) observe that, although higher ventilation rates can increase energy costs in relation to building operation, these can be reduced by several measures such as prudent and systematic maintenance of heating/ventilation/air-conditioning (HVAC) systems and by reducing superfluous pollution sources indoors

KEY ISSUES IN LITERATURE

In our review of codes and standards above, several key issues were identified. In this section we review the literature on those key issues.

DEFINITION OF CONTAMINANT SOURCES

Airborne indoor contaminants have two types of sources: indoor sources and outdoor sources. Indoor sources should be removed from the dwelling or the air contaminated by the source should be vented to outdoors as close to the source as possible, whereas outdoor sources should be removed from the air as much as possible before the air is brought inside the house. Indoor sources include mold and mites, carbon dioxide, indoor generated particulates, tobacco smoke, formaldehyde and other volatile organic compounds (VOC's), and combustion products. The chapter on the affect of ventilation on health in the Ventilation: A State of the Art Review (Santamouris, to be published) describes sources of air pollutants that affect human health, and is summarized with a few additions from other sources below:

Mold and mites both produce substances that are respiratory irritants and allergens. Both populations increase with increasing building humidity, so source venting of humidity (showers, and cooking) is important to reducing these allergens in the building. In climates and seasons when outdoor humidity is significantly higher than indoor humidity simple ventilation is not sufficient to control indoor humidity. Air conditioning systems are generally used to continuously dehumidify indoor air.

Water vapor and carbon dioxide are both products of metabolism, and are released during respiration. It is impractical to vent these pollutants at the source, so whole house ventilation is needed. This explains why many standards are written in terms of a minimum ventilation rate per person.

Indoor particulates are commonly known as dust. Particles with a diameter in the 0.1 μm to 0.5 μm range stay airborne the longest with a deposition loss-rate coefficient on the order of 0.1 h^{-1} . (Thatcher et al., 2002) Particle removal at this rate is could also be achieved by ventilation with an air change rate of 0.1 air changes per hour (assuming particle-free replacement air). Interestingly, the same size particles have the lowest deposition rate (about 20%) in the head airways and lungs. Deposition of particles in the lungs increases from 20% to 100% as particle size decreases from 0.1 μm to 0.001 μm . (Hinds, 1999) Dust particles on surfaces can become airborne by air currents and

activities in the room. Effective control of dust contaminants in the air requires a combination of removing dust from surfaces, ventilating air that has dust contamination, and filtering incoming air to remove dust from the exterior.

Tobacco smoke is most effectively controlled by removing the smoker from the house. The ventilation rate required to dilute tobacco smoke to a safe level is 555 l/s per a smoked cigarette in an hour (Santamouris, to be published). This rate is unreasonable to achieve in practice, and this is why the ventilation standards implicitly or explicitly do not address dwellings with smokers.

In the last ten years, research has shown that almost all materials (varnishes, paints, floor coverings, furniture, partitions, sealants, etc...) emit hazardous chemical pollutants. Rates of emission have reduced due to recent labeling systems, but ventilation is still necessary, particularly in new or recently remodeled dwellings to dilute the off-gassed chemicals.

Combustion products that are harmful to health are nitrous oxides (NO_x) and carbon monoxide (CO.) Carbon monoxide is formed in the case of incomplete combustion when not enough oxygen is supplied. Ideally, combustion products would be exhausted directly without mixing with inside air. This is how most water heaters and furnaces are designed, and generally function. Range hoods are necessary to exhaust combustion products of gas cook tops, although the capture efficiency of these hoods is generally about 60% (Santamouris, to be published).

Outdoor air brought into the building should contain as few contaminants as possible. This may mean filtering the air, or placing the inlet vents where they will not bring in contaminated air. Outdoor sources are pollen, combustion products, (nitrogen oxides, carbon monoxide), and ozone. Pollen can be easily filtered out of incoming air because the particle size is large. The most likely outdoor source of combustion products are gasoline powered cars and trucks. Combustion products are controlled by placing inlet vents away from roads, driveways, and parking lots. Ozone generally has a higher concentration outdoors than indoors. It may react with other compounds indoors resulting in harmful chemicals. Ozone can also be produced by electrostatic filters.

WHOLE-HOUSE VENTILATION RATES

Ventilation rates were first stipulated by a physician named Billings in the 1890's at a minimum whole house rate of 30 cfm per person (Roberson, 2004). The concern at this time was about airborne spread of diseases such as tuberculosis. This rate was adopted by the American Society of Heating and Ventilation Engineers (ASHVE) in 1914, although in this early version it was not clear what percentage of the ventilation air should come from outdoors. Subsequent research by Yaglou and others found that only 15 cfm per occupant of outdoor air was necessary (Janssen, 1994) to maintain acceptable air quality as perceived by visitors to occupied laboratory spaces. During the 1970's the American Society of Heating, Refrigeration, and Air-Conditioning Engineers, ASHVE changed names with the advent of refrigeration technology, adopted ASHRAE standard 62-1975 which reduced the recommended ventilation rate to 5 cfm per person. In the 1980's the accepted standard again became 15 cfm per person after experimental work by Ole Fanger showed that this level was necessary in order to control odors indoors. ASHRAE Standard 62-1989 specified a minimum ventilation rate of 0.35 ach or 15 cfm per person, whichever was greater.

The whole house ventilation may be provided by mechanical ventilation (local or distributed) or natural ventilation, i.e. unintentional openings (infiltration) or intentional openings (windows, passive vents). Each of these options are examined in more detail in the following paragraphs.

LOCAL EXHAUST RATES

The first local exhaust was a hole in the roof to let smoke out of the building. Fans were invented by Leonardo DiVinci circa 1500 (Kühnl-Kinel, 2000), however exhaust fans didn't become widely used until the 20th century (Kaplan, 1986). Exhaust rate regulations probably entered the standards as rules of thumb that were introduced into the building codes. Exhaust rates were first regulated by ASHRAE in Standard 62-2001.

AIR DISTRIBUTION AND DUCT LEAKAGE

Ventilation efficiency is a concept that has been discussed in the literature as the ratio of the integrals of the concentrations of tracer gas in the different zones (Maldonado, 1983). One zone is generally taken as the reference zone, and each of the other zones are compared to that zone. It has been found that when an air handler for a whole house air distribution system is running, the zones are well mixed, but when the air handler turns off the zones start to diverge. The rate of divergence depends on temperature and wind conditions as well as the physical characteristics of the building.

Ventilation strategies have been developed which use an exhaust fan at one location to extract air, and require an air distribution system to be turned on to evenly distribute the fresh air brought in through the building shell (Fugler, 2004). Although this strategy offers evenly distributed fresh air at a low initial cost to the builder, it has several drawbacks such as the excessive fan energy required to mix the air (most HVAC fans draw 500W), the likelihood that the HVAC fan will not be turned on as designed unless a control system exists to turn it on, and the energy penalty associated with duct leaks, which scales with the duration of HVAC fan operation.

Duct leakage can be a dominant source of ventilation in houses with tight building envelopes and leaky ductwork. When ductwork is located in an unconditioned space, air infiltration rates typically double when the air handler fan is turned on (Modera, 1989.) Unfortunately, ventilation air obtained in this manner has a high energy penalty. The energy penalty is greatly dependent on where the ducts are located (attic or crawlspace) and the climate that the house is located in, but a simplified hourly model predicts annual energy loss to be 3,500 kWh for attic ducts in Sacramento, CA and up to 10,000 kWh for the same ducts configuration in West Palm Beach, Florida (Modera, 1989.) Ventilation air obtained in this way will contain contaminants (particulate matter, VOC, radon, etc.) from the attic or crawlspace where the ducts are located.

INFILTRATION

Infiltration has historically been the main source of ventilation in residential buildings, and in some buildings it still is. There has been an ongoing debate within the research community over which type of ventilation is better. Liddament (2001) compares the two strategies in Table 4.

While it is a choice in building a new house, to make it tight or conventionally leaky, existing construction does not have this option. Very few existing houses are below the minimum recommended ventilation level, and in most houses it is difficult to seal them enough to bring them below this level.

The major problem with using a leaky building envelope to provide ventilation is that the direction of airflow is uncontrolled. Ideally, polluted air is exhausted from the house close to the source of pollution, and it enters the house evenly in all other areas. This airflow pattern is unachievable with a leaky envelope, even when exhaust fans are installed to aid in air extraction from rooms with source pollutants (Roberson, 2004). In addition, infiltration is wind and temperature driven so the magnitude of air exchange will change seasonally. This will lead to over-ventilation or under-ventilation during certain seasons. However, if the house has the right permeability to provide

good IAQ in winter, then additional ventilation can be provided by window opening in mild weather (Howard-Reed et al., 2002).

'Tight' Building	Possible considerations and/or points of attention	'Less Tight' Building
Mechanical extract and balanced ventilation systems can be dimensioned to perform reliably with minimum interference from prevailing weather conditions	Ventilation Strategy	Basic ventilation may be dominated by air infiltration Passive stacks and/or local extract fans, combined with user controllable trickle ventilators may be used to 'top up' ventilation.
Heat recovery systems can be effective.	Advantages	A measure of 'safe background' ventilation is provided by airflow through the natural porosity of the building
Uncontrollable draughts energy loss avoided.		Mechanical systems and heat recovery will perform unreliably because of interference from fabric leakage. Risk of excessive air change especially when driving forces are high (e.g. high temperature difference (winter) and high wind speeds.)
Severe risk of inadequate ventilation if occupant seals air supply return terminals or switches system off.	Disadvantages	
Fan energy needed either to overcome high under-pressure (e.g. 10-20 Pa room + 200Pa duct) with an extract system or to operate two fans (balanced system – e.g. 200Pa for each duct network)		
Method of purging needed, either by substantial ventilation boost or by openable windows	Control Strategy (People are not capable of correctly managing ventilation devices)	User can control trickle ventilators, fans and openable windows as needed
Adjustable ventilation grilles should not close completely since these represent the only significant source of air supply.		
Cooler climates where high infiltration losses lead to discomfort and energy loss and where the benefit of heat recovery can be maximized.	Applications	Milder climates where cold draughts are less of a problem and heat recovery is economically difficult to justify.
Outcome: By good design and with a thorough understanding of the interaction of air-tightness and climate with ventilation both approaches could lead to good air quality and energy efficient solutions.		

Table 4: Comparison of Tight Envelope versus Average Envelope with respect to Ventilation, Liddament (2001)

WINDOWS AND PASSIVE VENTS

Natural ventilation is the subject of one chapter of Ventilation: A State of the Art Review (Santamouris, to be published). The physics of airflow in urban areas is discussed in detail, and

examines the issues of noise and pollution as barriers to using natural ventilation in urban areas. Noise is attenuated by balconies and with increasing height above street level. After a certain threshold level, the level of pollution in an urban area is inversely related to the economic development of the area.

The main problem of using windows for ventilation is that occupants and weather conditions control the ventilation rate, and these are less predictable than a motorized fan. Occupants open windows generally to dilute odor in the dwelling, but research has shown that odor is not necessarily a good predictor of the need for ventilation since contaminants such as radon and carbon monoxide are odorless (Liddament, 1996). Window opening behavior varies among individuals, and with weather conditions so there is no way of ensuring that adequate ventilation is provided by window opening. When windows are open, however, they can ventilate the house as much as or more than infiltration caused by weather effects (Howard-Reed et al., 2002). Window opening in mild weather confounds the theory that natural ventilation is lower in mild weather.

Passive vents may be a solution for natural ventilation that is not controlled by the occupant. It has been shown that constant area passive vents either do not provide adequate ventilation in mild weather (spring and fall) or they over-ventilate in winter (Wilson and Walker, 1992). Some air inlets automatically adjust the size of the opening such that it is larger when the outdoor air is warm and smaller when outdoor air is cold. Other air inlets can be centrally controlled to open or closed in coordinated way with the other ventilation system components (Dorer, 2004). The Residential Hybrid Ventilation project (Dorer, 2004) proposes four hybrid (combined passive and active) ventilation systems, designed for severe cold, cold, moderate and mild climates. All of the designs propose outdoor air supplied to the living spaces and extracted from the bathrooms and kitchen, and all propose a central control system linked to occupancy and humidity sensors in order to provide just the ventilation that is needed and no more.

COMBUSTION EQUIPMENT

Substantial work has been done in the United States and Canada to understand backdrafting and spillage, and the relation of these events to the operation of ventilation equipment, but in spite of these efforts we still cannot reliably predict when backdrafting and spillage will occur, and if the quantity of contaminants released into the house will be harmful to the occupants (Nagda et al, 1995)

FILTRATION AND AIR CLEANING

Filtration is generally thought of as the solution to removing particulate pollution in indoor air. In “A Guide to Energy Efficient Ventilation” Liddament (1996) includes a chapter entitled “Air Cleaning by Filtration” where he describes types of particulates, and types of filters for addressing various particle size and chemical composition. He discusses the European rating system for filtration efficiency ranging from EU1 with a dust spot efficiency of 10% to 20% to EU14 that has a dust spot efficiency of greater than 90%. The equivalent rating system in the United States is the MERV rating, defined in ASHRAE Standard 52.2-1999. This scale ranges from MERV 1 with average particle size efficiency (E_3) of less than 20% to MERV 16 with E_3 greater than 95%.

Liddament refers to filtration systems for all types of buildings, but he gives the following requirements for an effective filtration system, which are applicable to residential buildings:

- It must not be used as a substitute for ventilation air needed for occupants, or for combustion appliances.
- It must be designed to remove the particular problem pollutant (e.g. Tobacco smoke, industrial emissions etc.).

- Recirculatory systems must have sufficient flow rate, e.g. two to three times greater than the ventilation rate to make a sensible reduction of pollutant concentration. This rules out any useful performance form desk top “air fresheners”.
- It must be well sited to intercept the polluted air.
- It must be inexpensive and easy to maintain, and preferably give a clear indication of when filter replacement or cleaning is needed.
- It should be free of operational noise.
- It should be energy efficient.
- It should not cause excessive draughts.
- It should be designed to ensure that filtered air is not directly short circuited back into the air intake.
- It should conform to relevant requirements and performance standards.
- Filters should be well sealed into the assembly frame to ensure that particles do not bypass the filter.
- Ductwork should have provision for cleaning. Contamination of a building with dust and bacteriological products can occur if ductwork and filters are not regularly cleaned.
- Air distribution across a filter should be uniform, otherwise local clogging and premature filter failure will occur.

A recent study by the Canada Mortgage and Housing Corporation (CMHC), Fugler (2000), shows that filtration may not be as effective as we think in removing pollutants from the air. The filter’s effectiveness is maximized when the filtration fan runs all the time, however, this is rarely the case in residences where the filter is generally part of the central heating and cooling system. In addition, airborne pollutants are increased by human activity such as getting out of bed, walking across the carpet, and making toast. People walk around in a “personal cloud” of pollutants, and furnace filters do little to reduce this cloud. Fugler recommends reducing particulates by:

- Removing footwear on entry;
- Keeping major dust generators (smoking, pets, and so forth) out of the house;
- Keeping dust collecting surfaces (open shelves, carpets, upholstered furniture) to a minimum;
- Vacuuming diligently and frequently with an efficient vacuum cleaner (a HEPA vacuum or a central vacuum work best at not re-blowing household dust back into the home.)
- Reducing the entry of particulate-laden outdoor air by closing windows , improving house air-tightness, and installing an intake filter on the air supply; and
- Using as effective a furnace filter as the homeowner’s budget permits.

NOISE ISSUES

The Home Ventilating Institute (HVI) publishes noise and energy use data for fans of their members (HVI, 2005). The results of these tests are reported on sones which is a psychophysical measurement of loudness, as opposed to a dB which is a physical measurement of sound power. Historically sound measurements were reported in dB (CAN/CSA, 1990). A study commissioned by the Canadian Mortgage and Housing Company and 10 other clients from the Institute for Research in Construction (Quirt, 1991) determined that the results of laboratory tests (in dB) used to determine ratings for fans are indeed representative of expected results for the installed unit. No criteria for "acceptable fan noise limits" were found in the literature.

ENERGY IMPACTS

Energy is of concern in ventilation in two ways: energy is required to operate the ventilation system, and energy is required to condition the air that is exchanged by the ventilation system. The first way to reduce energy costs for ventilation is to not over-ventilate by natural or mechanical means. Most of the existing housing stock is over-ventilated by infiltration (Sherman and Dickerhoff, 1994). An average infiltration rate of 29.7 air changes per hour at 50 Pascals was reported which corresponds to a natural air change rate of about 1.5². Most new houses are not over-ventilated by infiltration (Sherman and Matson, 2002). The average infiltration rate for new houses was found to be 5 air changes per hour at 50 pascals, corresponding to a natural air change rate of 0.25. Additional energy may be saved by recovering the heat in the exiting air stream. Research has shown that heat recovery in the building envelope from infiltration air is minimal in insulated walls (Walker and Sherman, 2003). Therefore, minimizing infiltration and supplying ventilation air with a ducted system can save energy by using a heat exchanger to condition the incoming air by removing heat from the outgoing air stream. Heat recovery ventilators are generally cost effective (and frequently used) in severe cold climates.

The energy required to operate a ventilation system can be minimized by making use of passive ventilation whenever possible and by decreasing fan energy by minimizing pressure drop in ducts by using larger diameter, shorter length ducts with a smooth interior surface. The Residential Hybrid Ventilation project (previously mentioned) (Dorer, 2004) gives examples of proposed hybrid (combined passive and active) ventilation systems that minimize the electrical energy needed to operate the ventilation system, as well as minimizing the ventilation rate by using occupancy and humidity sensors in order to provide just the ventilation that is needed for good indoor air quality.

In "A Guide to Energy Efficient Ventilation", (Liddament, 1996) the author devotes a chapter to the energy impact of ventilation and infiltration. He estimates the energy impact of ventilation (intentional and unintentional) for 11 European countries, the United States, and Canada. The delivered air change energy ranges from 40 GJ for the United States to 8 GJ in Sweden, with the majority of the countries using about 20 GJ.

Wray et al. (2000) examined the energy cost of four ventilation strategies: infiltration, central exhaust, heat recovery ventilator, and forced air-cycler system. They found that the lowest cost system, central exhaust only, would add a marginal cost of \$0.50 a day for a typical new house in the United States. This can be compared to the typical cost of \$2.00 a day to condition the infiltration air of a typical existing house. Designed passive ventilation systems and hybrid ventilation systems were not investigated.

² The natural air change rate is dependent on climate, represented by the variable N, which ranges between 16 and 24 for climates in the United States. The value of N=20 has been used for these conversions.

DISCUSSION OF LITERATURE GAPS

The most significant area where research is needed to fill gaps in our knowledge is in ventilation impact on electricity demand. This type of study would require detailed information about the exact times that the ventilation system is in use and the number of systems operating, thus making it difficult to carry out. The study would have to be linked to a specific ventilation standard or ventilation strategy and a specific geographic area.

KEY FINDINGS

Ventilation is increasingly becoming recognized as an important component of a healthy dwelling. The states of Washington, Minnesota and Vermont now require mechanical ventilation in dwellings, and the state of Maine is considering such a regulation. New guidelines from the American Lung association and Energy Star include mechanical ventilation requirements. Canada requires mechanical ventilation, and many European countries have a ventilation requirement that may be satisfied without a mechanical system.

All the ventilation standards tend to cluster around common values for recommended ventilation rates. Whole house ventilation rates are generally 0.35 ach, although some standards do stipulate values as high as 1.0 ach. Kitchens are often required to be vented at a rate of 50 l/s, intermittently or at some lower continuous value. The continuous ventilation requirement is as high as 30 l/s (in Canada and the UK) or as low as 6 l/s (in France.) Regulations for bathrooms are similarly prescribed with a higher intermittent rate, often 25 l/s, and a lower continuous rate, with a range of 15 l/s to 4 l/s.

Surveys of occupants showed that people generally think that ventilation is important, but that their understanding of the ventilation systems in their houses is low. The majority of people are satisfied with their ventilation systems. As to whether people actually use their ventilation systems, studies showed that 90% of passive ventilation systems were in use, as opposed to mechanical systems which are used much less often. The use of such systems varied widely between studies from 3% (bath fans) in a California study to 70% (exhaust only ventilation system) in a Canadian study to 82% (HRV system) in another Canadian study.

REFERENCES

- American Lung Association. 2004. "American Lung Association Health House Builder Guidelines." American Lung Association, Saint Paul, MN.
- ASHRAE. 1999. "ANSI/ASHRAE Standard 52.2-1999, Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size". Atlanta, GA; American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.
- ASHRAE. 1989. "ANSI/ASHRAE Standard 62-1989 - Ventilation for Acceptable Indoor Air Quality". Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
- ASHRAE. 2004. "ASHRAE Standard 62.1-2004 - Ventilation and Acceptable Indoor Air Quality". Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
- ASHRAE. 2004. "ASHRAE Standard 62.2-2004 - Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings". Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
- ASHRAE. 2001. "ANSI/ASHRAE Standard 90.2-2001, Energy Efficient Design of Low-Rise Residential Buildings". Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
- ASHRAE. 1994. "ANSI/ASHRAE Standard 119-1988 (RA 94), Air Leakage Performance for Detached Single-Family Residential Buildings". Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
- ASHRAE. 1993. "ANSI/ASHRAE Standard 136-1993, A Method of Determining Air Change Rates in Detached Dwellings". Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
- Bohac, D., M. Cheple. 2002. "Ventilation and Depressurization Information for Houses Undergoing Remodeling" Minnesota Department of Commerce State Energy Office
- California Energy Commission. 2005. "Title 24, Part 6, of the California Code of Regulations: California's Energy Efficiency Standards for Residential and Nonresidential Buildings." California Energy Commission, Sacramento, CA.
- CAN/CSA. 1991. "F326-M91 Residential Mechanical Ventilation Systems" Canadian Standards Association, Mississauga, Ontario.
- CAN/CSA. 1990. "C260-M90 Rating the Performance of Residential Mechanical Ventilation Equipment". Canadian Standards Association, Mississauga, Ontario.
- Council of the European Community (CEC). 2003. "Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings". Official Journal of the European Communities, Brussels, January 4 2003.
- Comité Européen de Normalisation (CEN). 2003. CEN prEN 14788. 2003. Ventilation for buildings: Design and dimensioning of residential ventilation systems, CEN, Brussels, 2003.

- Concannon, P. 2002. "Residential Ventilation". AIVC Technical Note 57. Air Infiltration and Ventilation Centre, Sint-Stevens-Woluwe, Belgium.
- Department of Housing and Construction. 2003. "D2 Finnish Code of Building Regulations, Indoor Atmosphere and Ventilation of Buildings, Regulations and Guidelines". Ministry of the Environment, Helsinki, Finland.
- Department of the Environment and the Welsh Office. "Ventilation, The Building Regulations 2000 Approved Document F 1995." Her Majesty's Stationary Office. Norwich, UK.
- Design Regulations BKR. 1998. "BFS 1998:38: Hygiene, health and the environment." Swedish Board of Housing, Building and Planning, Karlskrona, Sweden
- Devine, J. 1999. "Whole House Ventilation Systems Research Report". Washington State Ventilation and Indoor Air Quality Code report.
- Devine, J., Lubliner, M., and Kunkle, R. 1999. "Occupant Interaction with Washington State Ventilation and Indoor Air Quality Code mandated whole house ventilation systems: Telephone survey results." ASHRAE Transactions, Vol. 105, Part 2.
- Dorer, V., A. Pfeiffer, A. Weber. 2004. "Parameters for the design of demand controlled hybrid ventilation systems for residential buildings" Air Infiltration and Ventilation Centre. (RESHYVENT)
- Dubrul, C. 1988. "Inhabitant Behaviour with Respect to Ventilation – a Summary Report of IEA Annex 8". AIVC Technical Note 23. Air Infiltration and Ventilation Centre, Sint-Stevens-Woluwe, Belgium.
- EPA. 2005. "Energy Protection Agency Indoor Air Quality Specifications." Energy Protection Agency, Washington, DC.
- Florida, State of. 2001. "Florida Building Code, Section 409, Ventilation." Florida Building Commission, Tallahassee, FL.
- Fugler, D. 2004. "Analysis of Ventilation System Performance in New Ontario Houses" Research Highlight Canada Mortgage and Housing Corporation, Ottawa, Ontario.
- Fugler, D. 2002. "Compliance of Ventilation Systems Installed to meet Proposed Changes to the 1995 NBCC." Research Highlight Canada Mortgage and Housing Corporation, Ottawa, Ontario.
- Fugler, D. 2000. "Is it Worth Putting in a Better Furnace Filter?" Home Energy Volume 17, Number 3. May/June 2000. Berkeley, CA.
- Grimsrud, D.T. and Hadlich; D.E. "Residential Pollutants and Ventilation Strategies: Volatile Organic Compounds and Radon", ASHRAE Transactions 105(2), pp. 849-863, 1999.
- Hadlich, D.E. and Grimsrud; D.T. "Residential Pollutants and Ventilation Strategies: Moisture and Combustion Products", ASHRAE Transactions 105(2), pp. 833-848 1999.
- Hinds, William. 1999. "Aerosol Technology: properties, behavior and measurement of airborne particles" John Wiley and Sons, New York.

- Hill. 1998. "Field Survey of Heat Recovery Ventilation Systems." Research Highlight Canada Mortgage and Housing Corporation, Ottawa, Ontario.
- Home Ventilating Institute (HVI). 2005. "HVI Certified Products Directory". Home Ventilating Institute, Wauconda, IL
- Howard-Reed, C., L. Wallace, W. Ott. 2002. "The Effect of Opening Windows on Air Change Rates in Two Homes". Journal of the Air and Waste Management Association 52:147-159.
- ICC. 2003. "International Residential Code for One and Two-family Dwellings." International Code Council, Country Club Hills, IL.
- ICC. 2003. "International Energy Conservation Code." International Code Council, Country Club Hills, IL.
- Janssen, John E. 1994. "The V in ASHRAE: An Historical Perspective". ASHRAE Journal. August. Vol 36 no. 8, pg 126-132 American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA.
- Janssen, John E. 1999. "The History of Ventilation and Temperature Control". ASHRAE Journal. October. Vol 41 no. 10, pg 48-70 American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA.
- Kaplan, J. 1986. "Development of Material Safety Data Sheets" Proceedings of the 191st American Chemical Society national meeting. New York, NY.
(<http://www.phys.ksu.edu/area/jrm/Safety/kaplan.html>)
- Kelly, K., M. Brien, and R. Stemp. 1993. "Occupant use of Ventilation Controls and Humidifiers during Cold Seasons". Proceedings of Indoor Air '93 Vol. 5, pp.69-72.
- Klepeis, N., W.C. Nelson, W.R. Ott, J.P. Robinson, A.M. Tsang, P. Switzer, J.V. Behar, S.C. Hern, W.H. Engelmann. 2001. "The National Human Activity Pattern Survey (NHAPS) A Resource for Assessing Exposure to Environmental Pollutants". LBNL-47713. Lawrence Berkeley National Laboratory.
- Kühnl-Kinel, J. 2000. "The History of Ventilation and Air Conditioning: Is CERN up to Date With the Latest Technological Developments?" Proceedings of the Third ST Workshop, Chamonix, France. CERN Geneva, Switzerland.
- Lemaire M-C, Trotignon R. 2000. "Ventilation in the French Homes: Survey of the attitudes and Behaviour of Private Citizens". Proceedings of Innovations in Ventilation Technology, 21st Annual AIVC Conference, 2000.
- Liddament, M. 1996. "A Guide to Energy Efficient Ventilaion". Air Infiltration and Ventilation Centre, Sint-Stevens-Woluwe, Belgium.
- Liddament, M. 2001. "Occupant Impact". AIVC Technical Note 53. Air Infiltration and Ventilation Centre, Sint-Stevens-Woluwe, Belgium.
- Maldonado, E.A.B., J.E. Woods. 1983. "Ventilation Efficiency as a Means if Characterizing Air Distribution in a Building for Indoor Air Quality Evaluation." ASHRAE Transactions. Vol 89,

Part 2B, pp.496-506. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA.

McKone, T.E., and Sherman, M.H., 2003. "Residential Ventilation Standards Scoping Study." LBNL-53800. Lawrence Berkeley National Laboratory, Berkeley, CA.

Ministère de l'équipement, des transports et du logement. 1982. "Arrêté du 24.03.82 relatif à l'aération des logements." Journaux Officiels du 27 mars 1982, Paris, France.

Minnesota, State of. 2000. "Minnesota Rules Chapter 7672: Energy Code". Department of Public Service, Minneapolis, MN.

Modera, M.P., 1989. "Residential Duct System leakage: Magnitude, Impacts and Potential for Reduction," ASHRAE Transactions 95 (2): 561-569. LBL-26575.

Nagda, N.L., R. W. Krug and M.D. Koontz. 1995. "Depressurization, Backdrafting and Spillage from Vented Gas Appliances – A Literature Review". Report of ENERGEN Consulting, Inc. and GEOMET Technologies, Inc. to Gas Research Institute and Pacific Gas and Electric Company, GRI-95/0426. November.

NFPA. 1999a. "NFPA 54-1999 National Fuel Gas Code". Quincy, MA: National Fire Protection Association.

NFPA. 1999b. "National Fuel Gas Code Handbook" 4th Edition. Editor: T.C. Lemoff. Quincy, MA: National Fire Protection Association.

NRC. 1995. "National Building Code of Canada 1995." National Research Council Canada, Ottawa, ON.

Oseland, N. 1995. "Occupant Response to Passive Stack Ventilation: A UK Postal Survey." 16th AIVC Conference Proceedings, Vol 2. Air Infiltration and Ventilation Centre, Sint-Stevens-Woluwe, Belgium.

Phillips, T., E. Mulberg, P Jenkins. 1990. "Activity Patterns of California Adults and Adolescents: Appliance use, Ventilation Practices, and Building Occupancy". Proceedings, 1990 ACEEE Summer Study on Energy Efficient Buildings, Vol. 4. pp.187-196. Washington, D.C.: American Council for an Energy-Efficient Economy.

Quirt, J.D. 1991. "Field measurement of sound from residential ventilation fans". CMHC (client report prepared by the Institute for Research in Construction, National Research Council of Canada), Ottawa.

Roberson, J. 2004. "Effect of Building Airtightness and Fan Size on the Performance of Mechanical Ventilation Systems in New U.S. Homes: A Critique of ASHRAE Standard 62.2-2003". Master of Science Thesis, University of California, Berkeley.

Santamouris, Matteous, Ed. To be published. "Ventilation: A State of the Art Review." James & James, London, UK.

Seppanen, O., W.J. Fisk and M.J. Mendell. 1999. Association of ventilation rates and CO2

concentrations with health and other responses in commercial and institutional buildings, *Indoor Air* 9(4):226-252.

Seppanen, O., W.J. Fisk and M.J. Mendell. 2002. Ventilation rates and health. *ASHRAE Journal* 44(8):56-58.

Sheltersource, Inc. 2002. "Evaluating Minnesota Homes Final Report." Prepared for the Minnesota Department of Commerce.

Sherman, M.H., Chan W. R., 2004. "Building Airtightness: Research and Practice" LBNL-53356. Lawrence Berkeley National Laboratory, Berkeley, CA.

Sherman, M. 2004. "ASHRAE's First Residential Ventilation Standard" Submitted to Buildings IX Conf, Clearwater FL, LBNL-54331.

Sherman, M.H. and Matson, N.E. 2002. "Air Tightness of New U.S. Houses: A Preliminary Report " LBNL-48671 Lawrence Berkeley National Laboratory, Berkeley, CA.

Sherman, M., and Matson, N., "Residential Ventilation and Energy Characteristics", LBL-39036 Lawrence Berkeley National Laboratory, Berkeley, CA.

Sherman, M. and Dickerhoff, D. 1994. "Air-tightness of U. S. Dwellings.", LBL-35700 Lawrence Berkeley National Laboratory, Berkeley, CA.

Thatcher, T., A. Lei, R. Moreno-Jackson, R. Sextro, W. Nazaroff. 2002. "Effects of room furnishings and air speed on particle deposition rates indoors". *Atmospheric Environment* 36 (2002) 1811-1819.

Tsang, Andy and Neil Klepeis. 1996. "Descriptive Statistics Tables from a Detailed Analysis of the National Human Activity Pattern Survey (NHAPS) Data." Report for the National Exposure Research Laboratory, Las Vegas, NV, July 1996.

Walker, I.S. and M.H. Sherman. 2003. "Ventilation Technologies Scoping Study." LBL-53811 Lawrence Berkeley National Laboratory, Berkeley, CA.

Walker, I.S. and M.H. Sherman. 2003. "Heat Recovery in Building Envelopes." Proceedings AIVC BETEC Conference, Washington, DC, October 2003. INIVE eeig, Brussels, Belgium. LBNL-53484.

Wargoeki P., J. Sundell, W. Bischof G. Brundrett, P.O. Fanger, F. Gyntelberg, S.O. Hanssen, P. Harrison, A.Pickering O. Seppanen P. Wouters. 2002. Ventilation and health in non-industrial indoor environments: report from a European Multidisciplinary Scientific Consensus Meeting (EUROVEN) *Indoor Air* 12(2):113-128.

Washington State Building Code Council. 2000. "Washington State Ventilation and Indoor Air Quality Code." Washington State Building Code Council, Olympia, WA

Wiley, J., J.P. Robinson, T. Piazza, K. Garrett, K. Cirksena, Y. Cheng, G. Martin. 1991. "Activity Patterns of California Residents". Final Report to the Air Resources Board. Contract Number A6-177-33.

Wilson, D.J. and I.S. Walker. 1992. "Feasibility of Passive Ventilation by Constant Area Vents to

Maintain Indoor Air Quality in Houses.” Proceedings of Indoor Air Quality '92 Conference. Joint Conference: ASHRAE/ACGIH/AIHA. San Francisco, CA.

Wray, Craig. 2001. “Guidelines for Residential Commissioning” LBNL-48767. Lawrence Berkeley National Laboratory, Berkeley, CA.

Wray, C., Matson, N., Sherman, M., 2000. "Selecting Whole-House Ventilation Strategies to meet proposed ASHRAE standard 62.2: Energy Cost Considerations" LBNL-44479. Lawrence Berkeley National Laboratory, Berkeley, CA.