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Effect of Building Airtightness and Fan Size on the Performance of Mechanical Ventilation Systems in New U.S. Houses:

A Critique of ASHRAE Standard 62.2-2003

by

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1 Abstract

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As many countries have already done, the U.S. is now undergoing a transition from homes ventilated by infiltration to homes that need mechanical ventilation to provide outdoor air when windows are closed. The American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) developed, and the American National Standards Institute (ANSI) recently approved, a new residential ventilation Standard 62.2-2003, which would require many new homes to have a mechanical ventilation system. However, Standard 62.2 sizes ventilation fans in such a way that the tighter the home, and the more it needs mechanical ventilation, the less likely it is to receive the minimum ventilation rate of 0.35 air-changes/hour.

This thesis uses the multi-zone building airflow software model CONTAMW to compare hourly air-change rates in a typical new home during a typical meteorological year in the moderate climate of Houston Texas. Two building parameters are varied in this analysis: leakage area (or airtightness), and ventilation fan size. There are three leakage scenarios: typical new construction, energy-efficient new construction, and tightest construction in the U.S.—and three fan scenarios: no ventilation fan, exhaust fan sized according to Standard 62.2, and an exhaust fan sized to deliver 0.35 air-changes per hour—for a total of nine scenarios. Air-change results are analyzed for time spent under-ventilated, adequately ventilated, and over-ventilated, and for exhaust ventilation efficiency, which is defined as percent of total ventilation attributable to the fan.

Results indicate that exhaust fans sized according to Standard 62.2 improve ventilation only marginally in typical new construction, while energy-efficient or tighter homes would be significantly under-ventilated. This thesis suggests revising Standard 62.2 to: 1) size ventilation fans to ensure a minimum ventilation rate, regardless of house tightness, and 2) address the impact of tightness on ventilation system performance.

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5 Introduction

The quality of air inside residential buildings is important because most people spend half their lives at home, and one-third of it sleeping in bedrooms. Our need for adequate fresh air to breathe has always been balanced by the need to condition indoor space; too little outdoor air is unhealthy, but too much makes it difficult and expensive to maintain comfort. Residential energy codes and ventilation standards attempt to reconcile these needs. The harsher the climate the more difficult but important it is to achieve this balance, which involves controlling the supply of outdoor air.

The conditioning and ventilation needs of commercial buildings are load-dominated, in that they are determined by the number of occupants and other indoor sources of heat and pollution, such as electrical lights and equipment. Residential buildings, on the other hand, are skin-dominated, in that they have a much higher ratio of exterior surface area, or envelope, to number of occupants or other heat sources. Most commercial buildings have mechanical heating, ventilating, and air-conditioning—HVAC—systems, in which outdoor air is regularly provided by and often integrated with the mechanical system that conditions (heats and/or cools) indoor air. Yet while all residential buildings have some form of heating, and many have mechanical cooling (air-conditioning), very few have mechanical ventilation systems that regularly provide outdoor air and distribute it throughout the living area; in other words, homes usually have H&AC but no 'V' (Andrews 2002).

Until recently, air leakage through residential building envelopes usually provided enough outdoor air for occupants to breathe, and to dilute modest levels of indoor air pollutants. However, as a result of changing building materials and methods (particularly panelized products such as plywood and drywall), combined with energy conservative building codes and standards, envelope leakage has been reduced to the degree that residential indoor air quality has become a concern (Hollowell et al 1979). As has already largely happened in northern Europe, Canada, and Japan, the U.S. is undergoing a difficult but necessary paradigm shift from houses ventilated by infiltration to those tight enough to need mechanical ventilation to ensure an adequate supply of outdoor air. Not only are new American houses tighter then ever before, but there are more sources of indoor air pollution, and more reasons for people to keep their windows closed for longer periods of time.

Increased use of engineered wood products such as plywood and oriented strand board (OSB) for sheathing, cabinets, and furniture ensure that formaldehyde, for example, will be present in a house long after it is built and occupied (Awbi 1991, Grimsrud & Hadlich 1999, Sherman & Hodgson 2002). Other typical sources of indoor air pollution in new houses include attached garages; synthetic carpet, upholstery, drapery, and clothing; paint; vinyl; cosmetics; personal hygiene and household cleaning products; pets; and second-hand or environmental tobacco smoke. Excess indoor moisture is a common problem because it can support growth of biological allergens such as dust mites, and contaminants, including mold (ANSI/ASHRAE 2001, Fisk 2002).

Meanwhile, central AC has made it possible for more people to live comfortably in hot and/or humid climates, to the extent that it is now standard in new single-family houses. By 1999, 84% of new homes nationwide had central AC, and across the South and Southwest, where the majority of new houses are being built, the prevalence was 99% (ARI 2000). Increased reliance on air conditioning for cooling and dehumidification ensures that windows are closed during a larger part of the year. Yet even in mild climates or mild weather there are other reasons that people may keep their windows closed; these include seasonal allergies (from pollen), outdoor air pollution, outdoor noise, the need for acoustical privacy and physical security, and a dramatic rise in the incidence of asthma (Bassett 1992, Hadlich & Grimsrud 1999, McKone & Sherman 2003). In any case, when windows are closed in most new homes, outdoor air must be provided by some other means.

These factors prompted ASHRAE [1] to develop its first residential ventilation Standard 62.2-2003, which—to the extent that it is adopted by building codes—will require many new U.S. homes to have mechanical ventilation systems (ASHRAE 2003). The difficulty of this paradigm shift is evident in the fierce opposition of the homebuilding industry, among others, to the new Standard.[2]

U.S. homebuilders are notoriously averse to risk (some would say innovation), so it's no surprise they are reluctant to undertake the integration of, and liability for, a new and unfamiliar mechanical system into their homebuilding process. Moreover, the industry is increasingly being consolidated into large production homebuilding companies, whose success depends on keeping their costs low. Because even the simplest mechanical ventilation system—which is a single exhaust fan upgraded to run quietly and continuously—adds some cost to a home, it is anathema to production builders.

Nevertheless, no one can reasonably argue against the fundamental concern and ultimate goal of ensuring that air inside homes does not endanger peoples' immediate safety or long-term health. The challenge now is to bridge the gap between residential building science and homebuilding practice. The challenge of ventilation is described by Etheridge and Sandberg in the introduction to their 1996 book *Building Ventilation: Theory and Measurement*, which was written by scientists for an audience of (primarily) engineers concerned (primarily) with non-residential buildings:

> "In the experience of the authors, a person beginning a study of ventilation is faced with three major problems. First, there is a vast and ever-increasing literature on the subject…(T)he sheer volume of papers can be daunting, and somewhat annoying when one encounters the same paper in several different guises. Second, most papers and articles justifiably assume prior knowledge of the subject and it can then be very difficult to judge the value and relevance of the work. In a similar way papers may contain assumptions which are not discussed and which can lead to problems if they are not fully appreciated. Confusion can also arise when unnecessary definitions or 'jargon' are used. Third, the fundamentals of ventilation lie within the science of fluid mechanics, which is really the province of the mathematical physicist. This problem is perhaps the greatest of them all. The processes of ventilation are extremely complicated in physical and mathematical terms, yet it is necessary to simplify them for engineering purposes."

This thesis recognizes that building scientists now face an even greater challenge—and need—to enable residential contractors to design ventilation systems that effectively and reliably ensure home air quality, as opposed to nominally meeting some minimum code requirement. This is a tough job, of which adopting Standard 62.2-2003 is a first step. Yet the Standard already needs improvement, because it ignores the impact of house tightness on ventilation system performance. The efficacy of mechanical ventilation depends on building airtightness; in other words, not only do tight houses need mechanical ventilation, but mechanical ventilation also needs tight houses.

This thesis challenges the ability of whole-house exhaust ventilation fans sized according to ASHRAE Standard 62.2 to actually provide the expected minimum air exchange rate of 0.35

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[1] The American Society of Heating, Refrigerating, and Air-conditioning Engineers

[2] ASHRAE Standard 62.2-2003 is referred to in this paper as "Standard 62.2" or simply "the Standard."

AC/h (air changes per hour), considering the actual airtightness and infiltration rates of new U.S. houses. It also proposes a simple method for sizing unbalanced ventilation fans to assure this (or any other) minimum air change rate, and encourages tighter new construction in accordance with ASHRAE Standard 119, which establishes performance requirements for air leakage of residential buildings.

6 Background and Literature Review

Before discussing ASHRAE's new residential ventilation standard, it is necessary to describe the factors that affect the ability of mechanical ventilation systems to operate effectively in new homes. The first of these is the range of pollutants that mechanical ventilation can be expected to control.

6.1 Sources of Indoor Air Pollution

In high-occupancy commercial buildings such as schools, theaters, and restaurants, ventilation systems have historically been designed to control the level of carbon dioxide (CO_2), which people exhale whenever they breathe. CO_2 itself is usually not toxic except at very high concentrations ($\geq$ 3% or 30,000 ppm), but its accumulation is correlated with occupants' dissatisfaction with indoor air. Dilution of indoor air with outdoor air to $\leq$1,000 ppm CO_2 usually keeps the moisture and odors generated by the breathing of occupants within acceptable limits (ASHRAE 1989a, Janssen 1994).

Residential buildings, on the other hand, have relatively low occupancy, so CO_2 is less of a concern. In homes, the pollutants of concern can be broadly categorized into three types:

- occupant-source—generated by occupants (primarily moisture and odors),
- building-source—generated from non-occupant sources in the building, and
- outdoor-source—belonging or coming from outdoors (e.g., auto exhaust, radon, smog).

Occupant-source pollutants are the moisture, odor, and toxins generated by people as they bathe, wash, and cook. Because these activities tend to be localized and intermittent, these pollutants are best controlled not by dilution with outdoor air, but by intermittently exhausting them to outdoors (as necessary) from the rooms where they are generated: usually kitchens, bathrooms and laundry rooms. Most building codes require an operable window or exhaust fan in these rooms. Opening windows is a form of natural ventilation, while exhaust fans are a form of mechanical ventilation called 'local (or spot) exhaust.' Local exhaust supplements but does not constitute a whole-house mechanical ventilation system; rather, it is a form of source control designed to remove occupant-source pollutants before they mix with indoor air and require dilution by outdoor air.[3]

Besides occupant-source pollutants, most homes have significant amounts of other air pollutants that cannot be removed by local exhaust because their sources are neither local nor intermittent. These building-source pollutants include formaldehyde and volatile organic compounds (VOCs) emitted over time by building materials such as engineered wood products; and furnishings such as carpet, vinyl and upholstery (Awbi 1991). In addition, synthetic clothing, personal cosmetics and household cleaning products all contribute gaseous chemicals to indoor air. Emission rates for these pollutants vary according to indoor humidity and temperature, product source strength and age, degree of de/sorption to interior surfaces, etc. The best strategy for limiting these

[3] That local exhaust fans do not constitute a ventilation system is underscored by the fact that they are typically installed by the electrical contractor, not the residential heating and cooling (H&AC) contractor.

pollutants is another type of source control that involves excluding potentially toxic materials and replacing them with low- or no-emission alternatives. However, this exclusive or selective source control is not often practiced in the typical new U.S. houses with which this thesis is concerned. In any case, most building-source pollutants must be controlled (diluted) by a whole-house ventilation system.

Whether natural or mechanical, ventilation introduces outdoor air, which can contain more pollen, automotive exhaust, humidity, and photochemical pollutants than indoor air. When this is the case, outdoor air can be filtered and/or dehumidified before it is brought indoors. The (in)ability of various mechanical whole-house ventilation systems to control the source of as well as to filter or (de)humidify outdoor air is discussed under **Types of Ventilation Systems.**

Besides occupant-source pollutants best removed by local exhaust, and building-source pollutants diluted by whole-house ventilation, there are other potentially hazardous pollutants that need to be kept outdoors. These outdoor-source pollutants include radon gas and combustion products, particularly carbon monoxide (CO), oxides of nitrogen and sulfur, and particulate matter such as soot. Radon can be present in (and enter a house from) the ground or groundwater, as well as concrete and brick building materials. Attached garages, which are practically a standard feature in new single-family houses, are also a source of toxic pollutants, particularly automobile exhaust (including benzene, toluene, xylene, and carbon monoxide) that can easily enter a house through an open door, infiltration, or return-side leaks in any forced-air system components located in the garage (Furtaw et al 1993, Jackson 1991, Lindstrom et al 1995, Brook 1996, Wilbur & Cheple 1997). Whole-house ventilation systems cannot be expected to control hazardous pollutants that get indoors, but they should be designed to facilitate—or at least to not interfere with—systems designed to keep hazardous pollutants out of the house (Harrje et al 1989).

In homes with forced-air conditioning—i.e., the vast majority of new U.S. houses—the forced-air system itself can bring outdoor pollutants indoors. Return-side duct leakage introduces air from spaces in which the return ducts are located: usually the attic, basement, crawlspace, and/or attached garage. Air in these spaces often contains outdoor pollutants that should remain outdoors, such as dust, mold, and auto exhaust (Kurabachi & Otterman 1993, McKone & Sherman 2003).

Hazardous pollutants should be removed or controlled at their source; combustion appliances, including fireplaces and gas water heaters, should be sealed from the living space or adequately vented and safety-tested while all exhaust fans are operating. If radon is present in ground below a house, the foundation should have a separate (passive or mechanical) ventilation system designed to keep radon from entering the house. Any wall, floor, or door between a house and attached garage should be airtight, and the garage mechanically vented to outdoors. Forced-air handlers should not be located in attached garages, and any ductwork in attached garages should be airtight.

Second-hand or environmental tobacco smoke (ETS) can be toxic and carcinogenic (Nazaroff & Singer 2004), and presents a special problem in residential ventilation system design. The treatment of ETS by ventilation standards is described under **History of Ventilation Requirements**. Ideally, people would not smoke, or would at least smoke outdoors, as mandated for many commercial buildings, but of course people are free to smoke in their own homes. Yet homebuilders cannot be expected to anticipate the smoking behavior of future occupants, much less to design ventilation systems to accommodate various smoking scenarios (e.g., bad, worse, worst). Even if occupants are known to smoke, the cost of conditioning enough outdoor air needed to dilute ETS to harmless levels (which have yet to be determined, Wheeler 1999), would be prohibitive. In any case, the responsibility for non/treatment of ETS in homes ultimately rests with smokers and their families.

This section has established that local exhaust should remove most occupant-source pollutants, that whole-house ventilation is designed to dilute additional occupant-source and any building-source pollutants, and that whole-house ventilation systems should help keep outdoor pollutants outdoors. Next we describe the basic types of whole-house ventilation systems. It should be noted, however, that it is first necessary to clarify that in this paper 'ventilation' applies to conditioned, habitable or occupied space—*not* to roofs or unconditioned attics and crawlspaces, which are typically required by codes to be 'vented.' Also, 'whole-house ventilation' means replacing relatively small volumes of indoor air with outdoor air to maintain indoor air quality — *not* the 'whole-house fans' that are sometimes used to move large volumes of air overnight to facilitate cooling of people or buildings.

Even in this narrowed context ventilation covers a wide range of natural and mechanical processes. This paper will be as specific as necessary about the type of ventilation being discussed, based on the following descriptions. To begin with, anything *designed* to ventilate a whole house will be called a "ventilation system."

6.2 Types of Ventilation Systems

Two things are required for air to flow into or out of a space: a hole, and a driving force across it. Holes are either unintended (leaks) or intentional openings (windows, vents). Driving forces are either uncontrolled (wind and stack effect) or controlled (fans). Ventilation is air driven through building holes (intentional or not) by any driving force, while infiltration is air driven through building leaks by wind and stack effect. Therefore, infiltration is a form (or subset) of ventilation. To be precise, 'infiltration' is outdoor air that enters a building, and 'exfiltration' is indoor air that leaves a building due to wind and/or stack effect; however, 'infiltration' typically refers to both.

6.2.1 Natural vs Mechanical Ventilation

Ventilation can be driven by either natural or a combination of natural and mechanical means. Natural ventilation is indoor–outdoor air exchange that is driven by the natural forces of wind and stack effect, which is the effect of temperature on the density (and thus relative buoyancy) of air. Natural forces are always present, but they can be supplemented by the mechanical force of fans.

Natural ventilation can be either accidental and uncontrolled, or deliberate and controlled. Infiltration is natural ventilation that, from a human perspective, is accidental and uncontrolled. Operating windows, doors, and skylights is a common way of controlling natural ventilation. Opening windows is deliberate because it requires conscious effort; it is controlled because the size of the opening is adjustable; and it is natural because any movement of air through an open window depends on the wind and stack effect. To optimize their physical and mental comfort, people need to be able to open and close their windows as often and as much as they like, wherever they are. However, this thesis is concerned with the ability of mechanical ventilation systems to provide adequate outdoor air when occupants choose to keep their windows closed, for whatever reason, so the rest of this thesis assumes that windows remain closed.

Besides windows, another example of deliberate and controlled natural ventilation is a passive ventilation system, in which the location and size of openings in the building envelope are carefully designed to facilitate and moderate the wind and stack effects on a particular building, including its site, size, configuration, orientation, and microclimate. Passive ventilation[4] is often used to control the amount of outdoor air supply in cold climates such as northern Europe and Japan (Awbi 1991, Enai et al 1996, Axley 1999). However, passive ventilation systems are only feasible in very tight houses, and they require much more care and skill to design than mechanical ventilation systems. Therefore, the remainder of this thesis deals only with mechanical ventilation systems, which are much more likely (than passive systems) to be used in new U.S. houses.

Before turning to mechanical ventilation *systems*, which are *designed* to ventilate houses, it is necessary to discuss a type of mechanical ventilation that is accidental (some would say negligent), uncontrolled, unaccounted for, and much too common—ventilation by forced-air duct leakage. Numerous studies have documented the impact of forced-air system leakage on house infiltration, or air exchange rates. To summarize, in houses with forced-air systems, a significant amount of the leakage area is typically located in the forced air handler, plenums and ductwork; the percent of leakage area attributed to forced-air systems ranges from 5%–45%, but 30% is typical of existing homes (Cummings & Tooley 1989, Lambert & Robison 1989, Palmiter & Brown 1989, Palmiter et al 1991, Jackson 1991, Walker 1999). This problem is compounded, however, because the amount of outdoor air introduced by forced-air duct leakage is several times that caused by natural infiltration, because operation of the forced-air fan creates pressures across duct leaks that are much higher than the pressures created by wind and stack effect. Furthermore, duct leakage is seldom balanced between the supply and return sides. Excess leaks on the supply side push heated or cooled air into unconditioned spaces and depressurize the house, while excess return leaks pull unconditioned air into the system from wherever those ducts are located (e.g., attic, garage) and pressurize the house, or at least those rooms with a supply register. Forced air system leakage has tremendous impacts on operating efficiency and indoor air quality and should be (but seldom is) eliminated by sealing and/or locating all system components within conditioned space. Nevertheless, most new houses in the U.S. have forced-air duct systems and unfortunately, the vast majority of those systems leak; therefore, this thesis attempts to account for the impact of duct leakage on house air exchange rates.

Mechanical ventilation systems, which are *designed* to ensure regular indoor-outdoor air exchange, use electric fans to move air from one place to another. Fans are designed to deliver a given airflow rate at a given system static pressure, or resistance to airflow; the lower the system resistance, the higher the airflow delivered by the fan, and vice versa. Therefore, the actual (installed) system resistance (including dampers, ducts, grilles, etc) should be taken into account when selecting fans. For example, 'rated flow' corresponds to an assumed (usually low) system static pressure; if the actual system resistance is higher than assumed by the rating, the fan will deliver less than its rated flow. Unless otherwise noted, fan flows in this thesis are *delivered*—i.e., verified after installation.

6.2.2 Balanced vs Unbalanced Ventilation

Residential mechanical ventilation systems use either one or more fans to exhaust indoor air and/or supply outdoor air to a house. Balanced ventilation systems use both an exhaust and a supply fan, while unbalanced ventilation systems use either an exhaust or a supply fan. Exhaust and supply fans are functionally identical except for the direction of airflow, i.e., orientation to the living area.

'Balanced' systems are not actually balanced unless both fans move air at the same rate and time. When balanced, these systems do not change indoor pressure relative to atmospheric pressure.

[4] 'Passive ventilation' can also refer to designs that facilitate convective cooling of people and buildings.

They can be unbalanced either inadvertently, likely as a result of poor installation or maintenance, or deliberately, such as if a homeowner wants to seasonally pressurize or depressurize the house. Indoor pressurization (relative to outdoors) helps keep outdoor pollutants (including summertime humidity) from infiltrating, while depressurization in winter helps keep moist indoor air from being driven into exterior walls where it can condense on cold surfaces and increase the potential for rot.

Besides the potential to control indoor pressure, the principal advantage of balanced ventilation systems is the ability to incorporate a heat exchanger that transfers energy between outgoing indoor air and incoming outdoor air. Depending on the climate and the efficiency of the heat exchanger, such heat- or energy-recovery units can significantly lower the operating costs associated with conditioning ventilation air.[5] However, the energy costs associated with fan operation are higher than in unbalanced systems because two fans are running instead of one. Also, installation costs are among the highest not only because of two fans and a heat exchanger, but also because the exhaust airstream must be ducted from the kitchen and bathrooms, and the supply airstream must be ducted to living and bedrooms.

Balanced heat or energy recovery ventilation systems can be excellent, but they're also expensive and require considerable training, skill and time to properly select, install, balance, and maintain. They're most often specified by custom or owner-builders in either very cold or humid climates. In comparison, unbalanced ventilation systems are much easier and cheaper for homebuilders to install, and so are much more likely to be found in new U.S. homes (Kiel & Wilson 1987, Sibbitt & Hamlin 1991, WA State Energy Office 1993, Roberson et al 1998). Therefore, this thesis focuses on unbalanced ventilation systems.

6.2.3 Intermittent vs Continuous Ventilation

The principal advantage of mechanical ventilation over natural ventilation is that temperature- and wind-driven infiltration is inconsistent, while fans can operate continuously. This is important not only because people constantly need air to breathe, but also because continuous (non-stop) ventilation is much more effective than intermittent ventilation at reducing concentrations of indoor air pollutants, particularly those of constant source strength. This principle is more fully described in Feustel et al 1986, Hekmat et al 1986, Sherman & Wilson 1986, and Palmiter & Brown 1989.

To summarize, the less consistent the ventilation rate, the greater the difference between 'average ventilation rate,' which is used to evaluate the cost of conditioning ventilation air, and 'effective ventilation rate,' which is needed to evaluate the ability of ventilation to dilute pollutants. When ventilation is constant, as in "very tight houses (with continuous) exhaust ventilation," there is virtually no difference between average and effective ventilation rates (Sherman & Wilson 1986).

This principle is incorporated into ASHRAE Standard 136 (1993), ASHRAE Fundamentals (2001) and Standard 62.2–2003, which prescribes that ventilation systems that operate intermittently, instead of continuously, must be sized according to **Equation 1**:

$$Q_{fan} = Q_{req} / (\varepsilon \times f) \tag{1}$$

where: Q_{fan} = fan flow rate

[5] Heat recovery transfers sensible heat only, while energy recovery transfers both sensible and latent heat.

Q_{req} = ventilation air requirement (Q_{fan})
ε = ventilation effectiveness (from Table 4.2 of Std 62.2 or **Table 1**)
f = fractional on time.

Table 1. Ventilation Effectiveness for Intermittent Fans
from ASHRAE Standard 62.2–2003

Daily Fractional On-Time, f	Ventilation Effectiveness, ε
f ≤ 35%	0.33
35% ≤ f < 60%	0.50
60% ≤ f <80%	0.75
80% ≤ f	1.0

For example, in a 2000 ft^2 3-bedroom home, Standard 62.2 requires a mechanical ventilation rate of ≥ 60 cfm. If the ventilation fan operates 15 minutes each hour, it would have a fractional on-time of 0.25, an effectiveness of 0.33, and the fan would have to be sized to move over 700 cfm:

$$Q_{fan} = Q_{req} / (\varepsilon \times f) = 60\,\text{cfm} / (0.25 \times 0.33) = 727\,\text{cfm}$$

In the same house, if the ventilation fan runs 45 minutes each hour, it would have a fractional on-time of 0.75, an effectiveness of 0.75, and would have to be sized to move only about 100 cfm:

$$Q_{fan} = Q_{req} / (\varepsilon \times f) = 60\,\text{cfm} / (0.75 \times 0.75) = 107\,\text{cfm}$$

Clearly, the less time a ventilation fan operates, the less effective it is and the larger it needs to be to achieve the same whole-house ventilation rate as a much smaller fan that operates continuously. In the case of residential ventilation fans, bigger is not better. Not only are homebuilders adamant about minimizing the size and cost of fans they install, but residents are much more likely to object to the noise and drafts associated with large ventilation fans by not using or even disabling them.

One argument of this thesis is that residential ventilation fans should be as small as necessary to deliver the effective design ventilation rate, but no smaller. Ventilation systems should use the smallest, quietest, most efficient fan(s) possible, which means they should operate continuously. The benefits of continuous ventilation are so incontrovertible that it is difficult to understand why anyone would design a residential mechanical ventilation system that operates intermittently.[6] Therefore, the remainder of this thesis focuses on continuously operated mechanical ventilation.

6.2.4 Supply vs Exhaust Ventilation

Unbalanced ventilation systems use (one or more) fans to either supply (deliver) outdoor air to or exhaust (remove) indoor air from a house. Supply and exhaust systems differ primarily in:

- their ability to control the location or source of incoming air,
- their potential to filter and/or dehumidify incoming air,
- their effect on indoor pressure, relative to outdoors, and
- the degree of ducting required.

Supply ventilation draws outdoor air from a single location, carefully chosen for optimal outdoor air quality; e.g., it should not be too near the ground, driveway, garage, or exhaust vent locations.

[6] In fact, the next section explains that residential mechanical systems that operate intermittently for ventilation were not designed for ventilation, but for heating, cooling and recirculating indoor air.

Because all incoming air passes through the supply ventilation fan, it is possible to filter outdoor air before it is distributed to the house; this is important for the growing number of people with asthma, allergies, and chemical sensitivities, or whose outdoor air may be significantly polluted.[7] If a house is tight enough, the air delivered by a supply ventilation fan will pressurize the indoor space, which not only does not interfere with the venting of any indoor combustion appliances but also helps keep outdoor air, humidity, and pollutants (e.g., radon, auto exhaust) from infiltrating.

Exhaust ventilation removes indoor air, which is replaced by outdoor air that enters by infiltrating through paths of least resistance. It is not possible to filter or to control the sources of incoming air, which may as likely come from the attic, foundation, or attached garage as from outdoors; also, outdoor air can contain unacceptable levels of pollutants, such as dust, relative humidity, and smog. If a house is tight enough, an exhaust ventilation fan significantly depressurizes the indoor space; such depressurization facilitates infiltration of air and pollutants (including those from the attic, foundation, or garage) and can also interfere with venting of indoor combustion appliances, if any.

In an often misguided attempt to control the source of incoming air with an exhaust ventilation system, some people install passive vents in a window or exterior wall of each living and bedroom; they may even call them "inlet vents," falsely assuming or implying that only outdoor air will enter through them (WA State Energy Office 1993, Reardon & Shaw 1997, EDU 1999a, US DOE 2002, EDU 2002). This technique was developed—and is necessary and appropriate—in the extremely airtight houses of Sweden, whose building code sets an upper limit on air leakage corresponding to 3.0 air-changes per hour at 50 pascals (≤ 3 ACH50). However, passive vents are designed and rated to admit a certain amount of outdoor air when the house is depressurized to at least 5 or 10 pascals. Unless a house is tight enough to be significantly and constantly depressurized by a small (50–100 cfm) continuous exhaust fan, these vents impair rather than facilitate the effectiveness of exhaust ventilation. This is because when stack effect is stronger than the fan, air is as likely to exit as to enter a house through these (or any other) vents, depending on their location relative to other leakage sites (Hekmat et al 1986, Reardon & Shaw 1997, Shapiro et al 1999, EDU 2002). Even vents with a damper designed to ensure one-way flow (outdoors to indoors) can leak when closed in response to stack effect, which is strongest when ventilation is least needed.

Exhaust ventilation should not be used in houses where depressurization poses a safety or health hazard, and passive vents should not be part of an exhaust ventilation system unless the house is proven (through leakage and pressure testing) sufficiently airtight to be significantly depressurized by an appropriately–sized continuously operated exhaust ventilation fan; otherwise passive vents contribute only leakage area (Shaw 1987, Bower 1995, CMHC 1996, EDU 2002).

Supply and exhaust ventilation systems also differ in the degree of ducting required. It isn't enough for a supply ventilation fan to introduce outdoor air at a single location; it must be distributed by ductwork to bedrooms and living areas (where people spend most of their time at home), and the supply fan must be sized to overcome the additional resistance of the filter (if any) and ductwork. With exhaust ventilation, incoming (though not necessarily outdoor) air is uncontrollably 'distributed' through the house according to the locations of infiltration sites (i.e., the paths of least resistance) and the exhaust fan. Exhaust ventilation is either 'single-port' or 'multi-port,' If multi-port, one remotely–located (vs ceiling-mounted) exhaust fan is ducted to all rooms that require local exhaust, i.e., each bathroom and the kitchen. This significantly improves distribution of ventilation air (since air is now exhausted from several locations instead of one)

[7] Because balanced ventilation systems include a supply fan, they also can filter incoming outdoor air.

and may or may not improve the source of incoming air, which remains uncontrollable (Reardon & Shaw 1997).

6.2.4.1 Forced-Air Supply Ventilation

Because of the need to distribute supply ventilation air to living and bedrooms through ductwork, some builders use the forced-air conditioning system fan and ductwork (which is present in any home with central air-conditioning) to distribute ventilation air as well. Such 'forced-air supply' or 'forced-air integrated' ventilation systems depend on operation of the forced-air fan to pull outdoor air into the forced-air duct system and distribute it to all rooms with a supply register. Compared to installing a separate supply ventilation fan and ductwork, it is much cheaper and easier for builders to install a 6" supply duct between an exterior wall (i.e., outdoors) and the forced-air duct system.

However, there are several significant problems with using a forced-air fan to provide ventilation. The first problem is that fresh air is needed all the time, while conditioning is not, so the forced-air fan must operate regularly for ventilation even if the thermostat does not call for heating or cooling. Yet because forced-air fans are designed to move roughly ten times as much air as is needed for ventilation (~1,000 vs 100 cfm, respectively), their operating costs are correspondingly larger, and the fact that the fan must operate more often further increases costs. One way to keep forced-air supply operating costs from being prohibitively expensive is to operate a high-efficiency variable-speed forced-air fan at low speed for ventilation; however, the better fans are also more expensive, so production builders use another option, which is to operate typical forced-air fans intermittently.

For example, the Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) sponsors the Building America Program, which attempts to improve the energy-efficiency of new homes by collaborating with and changing the construction practices of production homebuilding companies. Building America sponsors several independent but related teams, each with its own strategy for demonstrating building strategies that save energy *at no net added cost to production builders*. One of Building America's teams is the Building Science Consortium, led by Building Science Corporation (BSC), and one BSC engineer "is the exclusive licensee of the applicable patents" to the accessory control (~$125 each, $200 installed) needed to operate a forced-air fan intermittently at regular intervals for ventilation (Rudd 2004). Not surprisingly, forced-air supply ventilation systems using this particular control device are installed in virtually all new homes built by production homebuilding companies working with Building Science Corporation within the Building American Program (EDU 1997, Barley 2001, Andrews 2002, EERE 2004, Rudd 2004). In fact, in spite of the inherent inefficiency of operating a forced-air fan even intermittently for ventilation, Rudd and his company recommend his product for use not only with forced-air supply ventilation, but also in conjunction with other types of ventilation systems, including continuous exhaust, supply, and balanced heat recovery (EDU 1999, Rudd 2004).

The Building America Program is doing its best to reconcile the need for ventilation of new homes with the current resistance of builders, the lack of public awareness on this issue, the ambiguity of ventilation standards (described below), and the dearth of home mechanical ventilation systems that are both affordable and effective. According to one program employee (Barley 2002):

> "(M)ost homebuyers are not fully aware of IAQ (indoor air quality) issues and whole-house ventilation requirements, and are thus not willing to pay the incremental cost of improved

> systems. Because the applicable standards do not require these improvements, lower-performance systems are often installed despite the best intention of engineering teams."

Nevertheless, from homeowners' or occupants' perspective (whether they realize it yet or not), there are other significant potential disadvantages to using a forced-air fan for ventilation. These are described elsewhere (Jackson 1991, Roberson et al 1998) but summarized here, with help of a Department of Energy document (US DOE 2002). Of forced-air integrated ventilation, it says:

> "To be most effective, heating and cooling ductwork must be airtight or located within the conditioned space of the house. Several design issues must be addressed, the solutions to which often come at the cost of increased system complexity.
>
> "Ventilation systems that use the air-handler fan tend to provide the most mechanical ventilation in the winter, when the cost of tempering outside air is highest and it is least needed because natural ventilation is usually greatest.
>
> "Ventilation systems that use the air handler fan also tend to provide the least mechanical ventilation when it is most needed…(which is why a non-thermostatic fan control is needed.)
>
> "Running a large air-handler fan can be noisy and expensive. One solution is to use a more expensive variable-speed air-handler fan that operates at low speed when heating or cooling is not needed. This approach may require a motorized damper to keep the ventilation rate nearly constant when the fan operates at different speeds. Another solution is to use a smaller, separate fan to pull outdoor air into the ductwork and distribute it throughout the house.
>
> Duct systems that distribute heated and cooled air effectively when the air flow rate is 800 cfm or more may distribute is poorly when the flow rate is dropped to 100 cfm of less."

In addition, not only is intermittent ventilation much less effective in controlling indoor pollutants, but it also does not maintain indoor pressurization, which is a key advantage of supply ventilation. The entire duct system should be within conditioned space because if not, when it leaks, "outdoor" air is as likely to come from wherever the return ducts are located (e.g., the attic, basement, garage) as from the supply air duct, and conditioned air is as likely to be distributed to wherever the supply ducts are located (e.g., the attic, basement, garage) as to the living area. Also, if supply duct leakage to outside exceeds return duct leakage (i.e., if more air leaks out of the supply ducts than leaks into the return ducts), the house can be depressurized—rather than pressurized—by the fan.

In any case, the expense of operating even a relatively efficient forced-air fan at intervals for ventilation is still higher than that of operating a quiet, efficient, right-sized supply ventilation fan continuously (Wray et al 2000). As homebuilders are just beginning to learn how to implement the 'V' in residential "HVAC," they might benefit from the experience of the commercial HVAC industry, which is at this same time beginning to reconsider the wisdom of using a single system to both condition indoor air and supply outdoor (ventilation) air. Both the following passages relate to the complexities and problems of ventilating commercial buildings with integrated variable-air-volume systems:

> "The solution…is to revisit the basic premise; to approach the design with a clean sheet of paper, the laws of physics, and a clear definition of the design parameters. Designers should begin with these, and the fundamental rules of design engineering philosophy, one of which was best stated by Albert Einstein: "Everything should be made as simple as possible but not simpler." An example of one solution...is the (building mechanical) system which basically separates the ventilation system from the environmental comfort system." (Coad 1996)
>
> "…(t)he key to finding a good (IAQ, or pollutant) dilution solution must address one fundamental challenge: decouple the traditional dual functions of maintaining thermal environment and providing needed ventilation." (Khattar 2002)

Fortunately, the advantages of supply ventilation can be achieved without using forced-air systems, as described in earlier reports (Reardon & Shaw 1997, Roberson et al 1998, Roberson 2000), by using a small efficient supply fan to continuously filter and deliver outdoor air to each bedroom and living area. Unfortunately, few builders are willing to try this independent 'multi-port supply system' because it requires some design and its own ductwork, which increases installation costs.

6.2.4.2 Single-Port Exhaust Ventilation

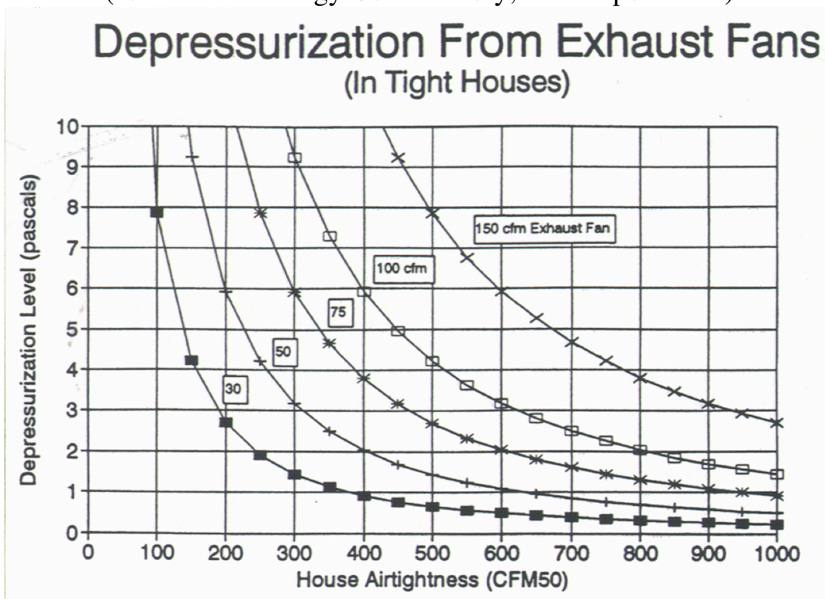
In spite of the prevalence of forced-air supply systems in some DOE/Building America projects, the easiest, least expensive and therefore most popular whole-house ventilation system is, and will likely continue to be, exhaust ventilation, and more specifically, single-port exhaust ventilation (Palmiter & Bond 1991, Sherman & Matson 1997, Wray et al 2000). Multi-port exhaust systems, which use a remote fan to remove air from each bathroom and kitchen through a set of ventilation-only ducts, provide better air distribution but cost more to install for the same reason as multi-port supply systems (Reardon & Shaw 1997, Roberson et al 1998). Single-port exhaust, on the other hand, not only has the lowest installation cost (see **Ventilation Costs**), but its operating cost is also low, even when operated continuously, because any appropriately-sized fan designed for quiet continuous operation is also relatively efficient. However, besides the critical inability to filter or control the source of incoming air (Wray et al 2000), single-port exhaust systems have other limitations; the first is related to depressurization hazards, the second to poor air distribution.

Like forced-air supply ventilation, single-port exhaust ventilation systems were not designed to provide whole-house ventilation; rather they were designed for a very different purpose and later, because of their familiarity and ubiquity, adapted (or adopted) to meet a new and unfamiliar need. Single-port exhaust ventilation systems are just upgraded local exhaust fans. For local exhaust fans to be effective (in removing moisture and odors from bathrooms and kitchens before they mix with indoor air), they need to be able to move air from a single room to outdoors; this is most successful if the room is isolated from the rest of the house by a closed—e.g., a bathroom—door. However, for a whole-house exhaust ventilation fan to be effective in pulling outdoor air into all rooms, it must significantly and continuously depressurize the entire house. This simple statement is a central tenet of this thesis, because is not yet well understood or fully appreciated in the U.S.

Residential building scientists should be aware of the relationship between tightness of a building and its ability to be depressurized by an exhaust fan. One of their most commonly used tools is a 'blower-door,' which measures the airflow required to depressurize a house to a given 'pressure,' i.e., indoor–outdoor pressure difference. **Figure 1** is from the Energy Conservatory, a leading manufacturer of blower-doors and other building diagnostic equipment. (Blower-doors and CFM50 are described in detail in **Airtightness of New U.S. Houses**.)

Naturally-induced infiltration creates indoor-outdoor pressure differences of just a few pascals; when infiltration is very low, exhaust fans are required to generate larger pressures, and airflows, **Figure 1** shows that the tighter the house (the lower the CFM50) the smaller the exhaust fan required to depressurize the house by a given amount; similarly, the tighter the house, the more it will be depressurized by an exhaust fan of a given size. This is basic residential building science.

Figure 1. Relationship Between Building Tightness, Depressurization, and Exhaust Fan Size
(source: The Energy Conservatory, Minneapolis MN)



Nevertheless, two apparently inseparable yet fundamentally conflicting assumptions about exhaust ventilation pervade American technical literature on residential mechanical ventilation. They are that:

1) an exhaust ventilation fan works (i.e., ventilates a house) by depressurizing the house to the extent (at least 5 to 10 pascals) that it pulls outdoor air in through leaks or vents, and
2) depressurization caused by an exhaust ventilation fan is so insignificant (<3–5 pascals) that it poses no hazard, e.g., by pulling combustion appliance exhaust or radon indoors.

Both statements cannot be simultaneously true. For a given space, time, and set of conditions (outdoor temperature, wind, interior door positions, operation of other fans), a given size exhaust fan (delivered cfm) either depressurizes a space by a given number of pascals (e.g., 5) or it doesn't.

For example, consider the assumptions, analysis, and conclusions of a field study in Vermont of single-port "exhaust only ventilation (EOV)" systems in typical new single-family homes with and without passive vents (Shapiro et al 1999). In its introduction, the report explains:

> "When the EOV is running, the house, or portions of it, are put under a slight negative pressure relative to the outdoors, and hence outdoor air comes through openings in the building."

After measuring the relative indoor pressure in houses with an exhaust ventilation fan (average 95 cfm rated, 63 cfm measured) the report, in its Performance Summary section, observes:

> "The ability of an exhaust fan to ventilate a house depends on its ability to depressurize the house relative to outdoors (causing) outside air to be brought in for ventilation. Depressurization can also cause backdrafting of natural draft combustion devices when it occurs with significant magnitude. Therefore, the ability to depressurize determines how well the EOV can introduce outdoor air into the house as well as its capacity for interfering with combustion devices.
>
> "The pressures achieved by these tests were low relative to pressures induced on a house by natural forces including temperature difference driving a stack effect or the wind… As a comparison, calculations of natural infiltration often use a seasonal average of 4 pascals as the magnitude of these forces (which) are 4 times greater that the pressure effects created by the

> EOV… averaging –1 Pa…(This) suggests that the EOV fans studied would have difficulty causing sufficient negative pressures throughout the house to assure that outdoor air will be introduced uniformly in sufficient quantities in habitable rooms as the result of fan operation."

In relating depressurization by exhaust ventilation fans to airtightness, it also observes:

> "In order for an EOV to induce enough pressure in passive air vents for them to consistently act as adequate air inlets, houses would have to be built tighter than even the tightest homes are being built today… Another way in which the EOV could induce enough air through the passive vents is to increase the size of the exhaust fan in the range of 175-200 cfm. However, this would over-ventilate the house (due to the natural leaks coming in through locations other than the passive vents), (and) create depressurization problems if there were atmospheric combustion appliances."

However, in its Conclusions, the same report states, among other things, that:

> "Exhaust-only fans can provide total exhaust air flows to meet a criteria such as 15 cfm per person, even in tight houses." and,
>
> "The magnitude of depressurization caused by the EOV systems makes it unlikely that EOV fans of the size found in this study, *by themselves* (italics original), will cause backdrafting of natural gas combustion appliances."

Both of these conclusions cannot be true. In this case, the first conclusion is erroneous; houses that are not tight enough to be depressurized by an exhaust ventilation fan may be adequately ventilated, but most of their ventilation is from uncontrolled infiltration, not the exhaust ventilation fan, which *seems* to be (and people assume it is) working because it makes noise and uses energy.[8,9]

Again, the preceding example is far from an anomaly, but rather a pervasive misconception. Here is another example, this from an Oregon extension agent describing the hazards of depressurization (Brook 1996):

> "It is generally accepted that depressurization of –5 pascals or more can cause problems for natural draft appliances… Continuous depressurization may be caused by forced air systems or whole-house ventilation systems. Less harmful intermittent depressurization may be caused by exhaust fans, clothes dryers, and other exhaust devices rated greater than about 160 cfm."

The first sentence is true, but there are several problems here. First, any de/pressurization caused by a forced air system is not continuous, but intermittent—whenever the forced air fan operates. Second, in the last sentence, presumably "depressurization caused by exhaust devices rated greater than ~160 cfm" is "less harmful" not because it's less severe (it isn't) but because it's intermittent (less often). But the real problem with this paragraph is the contradiction between the statement that it takes "exhaust devices rated greater than ~160 cfm" to depressurize the house, and the statement that "continuous depressurization can be caused by whole-house ventilation systems," whose fans are seldom larger than 100 cfm. The writer, like so many others, understands that exhaust ventilation works by depressurizing a house, but doesn't fully appreciate the corollary —that exhaust ventilation doesn't work *unless* it significantly depressurizes a house.

If an exhaust ventilation fan doesn't depressurize a house, it may be running but it's not *working*. In other words, if an exhaust ventilation fan can't depressurize a house, it can't ventilate it either. An exhaust fan must overcome natural forces in order to control indoor-outdoor air exchange. If

---

[8] The statement might be true if the phrase "even in tight houses" were changed to "only in tight houses."

[9] It would have been interesting to measure pressures in each house with and without the EOV fan running.

the house isn't tight enough and/or the exhaust fan isn't big enough, the house is ventilated mainly by natural infiltration, while the fan uses energy and perhaps nominally meets a code requirement. This is only a slight over-simplification, the full explanation of which is the subject of this thesis.

Exhaust ventilation systems should be effective—in other words, they should work—which means they should be able to depressurize a house. Therefore, they should not be used in homes where depressurization poses an immediate safety or longer-term health hazard, including houses with an attached garage, subsurface radon, or a natural-draft (vs sealed combustion or actively-vented) fireplace, furnace, or water heater. Full discussion of depressurization hazards is beyond the scope of this thesis; readers are referred to the checklist in **Appendix A**, and to Harrje & Gadsby 1986, Brook 1996, Roberson et al 1998, and Nelson 2000.

Exhaust ventilation systems are common and have proven to be effective in Scandinavia, where most houses are electrically heated and very tight (Nylund 1980**)**. They are also common (among houses with ventilation systems) but proven *not* to be effective in the Pacific Northwest and Vermont, where most houses are heated electrically or hydronically, respectively, but are not very tight (EDU 1999a, Shapiro et al 1999, EDU 2002). Even in Canada, where houses are tight compared to those in the U.S. (see **History of Ventilation Requirements)**, houses are still not tight enough for exhaust ventilation to effectively distribute ventilation air, with or without passive vents (Reardon & Shaw 1997). This brings us to another significant limitation of single-port exhaust ventilation systems: they are much more susceptible to the impact of closed interior doors than are supply or balanced systems, in which ducts deliver outdoor air to each room.

For exhaust ventilation to be effective, the fan must affect the pressure in each room so outdoor air enters through leaks or vents. This means the fan must 'communicate' with the air in each room. Even in a tight house, movement of air from each room to the exhaust fan can easily be disrupted by closed interior doors, unless the doors are deliberately and substantially vented and/or undercut. Typically, however, if the exhaust ventilation fan is centrally located (e.g., in a hall or stairway) and bedroom doors are closed at night, the people sleeping in those bedrooms will not receive ventilation as a result of the exhaust ventilation fan. They may, however, receive ventilation air as a result of stack effect (if the house is leaky), or duct leakage (if and when the forced-air fan runs). This limitation of exhaust systems is more thoroughly characterized elsewhere; for more detail, I suggest the following: Haghighat et al 1990, Kesselring 1991, Reardon 1995, Sawachi et al 1998.

Perhaps the best and most complete analysis of the relationship between building airtightness and the effectiveness of exhaust ventilation systems is from Japan. In 1998, Sawachi et al published a series of reports on experiments conducted in a full-scale model of a two-storey house built within an artificial climate chamber; the variables controlled were indoor-outdoor temperature difference, building airtightness, leakage distribution, and interior resistance to airflow (from doors, mainly). One report was devoted to the performance of single-port "nonduct" exhaust ventilation systems, which "are found in almost all dwelling units in Japan." From the abstract of their second report:

> "From experimental results, it has been demonstrated that in an extremely airtight house, stable ventilation almost unaffected by an internal-external temperature difference can be achieved by a nonduct exhaust-only ventilation system with a single exhaust fan continually operated, if suitable door undercuts are provided. It has also been verified that at a certain low level of airtightness (*Ed: i.e., higher leakage),* the system does not work efficiently, and that in a house where the area of cracks in the envelope is too large, sufficient negative pressure cannot be

> generated by a single fan. Such a house is, therefore, unsuitable for being ventilated by the exhaust-only technique."

Regardless of their (in)ability to effectively ventilate new U.S. houses, exhaust ventilation systems remain the easiest and cheapest way for builders to meet the new ASHRAE residential ventilation Standard. Because unbalanced exhaust ventilation systems are likely to be the most common type of residential mechanical ventilation system, they are the focus of this thesis.

6.3 New Home Construction in the U.S.

The new residential ventilation standard ASHRAE Standard 62.2–2003 is titled *Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings*. In its *Section 2. Scope,* Standard 62.2 says it applies to "single-family houses and multi-family structures of three stories or fewer above grade, including manufactured and modular houses (ASHRAE 2003). This thesis also applies to those residences, but focuses on detached, site-built, single-family houses, most of which are centrally heated and air-conditioned, and whose floor areas and ceiling heights continue to rise.

According to the U.S. Census Bureau, approximately 1,677,700 new privately-owned housing units were completed during 2003.[10] Of those, 45% were built in the South, 26% were built in the West, 20% were built in the Midwest, and 9% were built in the Northeast. **Table 2** provides more detail on characteristics of new single-family houses completed during 2002 (US Census 2004). A map of Census regions (Midwest, Northeast, South, West) and divisions is available online at: http://www.eia.doe.gov/emeu/reps/maps/us_census.html .

Table 2. Selected Characteristics of New Single-Family Houses Completed in 2002
Source: U.S. Census Bureau: www.census.gov/const/www/charindex.html

Housing Characteristic	All U.S.	South	West	Midwest	Northeast
median floor space, ft^2	2,114	2,120	2,127	1,979	2,330
average floor space, ft^2	2,320	2,317	2,350	2,209	2,516
foundation: slab-on-grade	50%	66%	63%	17%	8%
foundation: basement	34%	15%	18%	75%	89%
foundation: crawlspace	16%	20%	19%	8%	3%
more than 1 story	53%	48%	54%	51%	84%
at least one fireplace	58%	53%	64%	60%	61%
air-conditioned	87%	99%	66%	89%	77%

For the country and each major region the average floor area of new homes ranges from ~2,200 to ~2,500 ft^2, with an average of 2,320 ft^2. The trend toward larger homes has been consistent; not only has average floor area increased by over 50% since the 1970s, but as of 2002 over 40% of new homes had an average ceiling height of at least nine feet (JLC 2002a).[11]

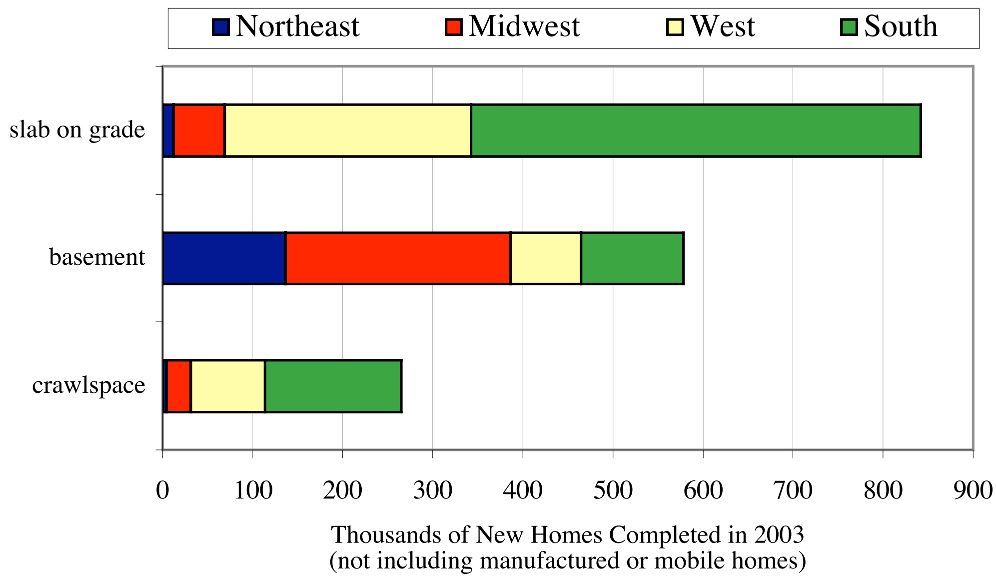
Eighty-seven percent (87%) of all new homes and 99% of those in the South have air-conditioning. Fifty percent (50%) of all new single-family houses have slab foundations; in the South and West, the percent with slab foundations increases to 66% and 63%, respectively. In all regions the majority of new single-family houses have a fireplace and about half are more than

[10] This includes an unknown number of "high-rise" units, but not manufactured or mobile homes.
[11] This number accounts for the prevalence of cathedral or vaulted ceilings, 2-storey foyers, etc, in homes.

one storey, (except in the Northeast, where the percentage is 84%). The Census records the number of parking spaces per garage, but unfortunately, not whether garages are attached or detached from the house.

Figure 2 shows the regional distribution of slab-on-grade, basement, and crawlspace foundations obtained by applying the detailed characteristics of single-family houses completed in 2002 to the total number of housing units (except manufactured homes) completed in 2003.

Figure 2. Number of Residential Units Completed in 2003 by Foundation Type and Region
Source: U.S. Census Bureau: www.census.gov/const/www/charindex.html
and www.census.gov/const/www/newresconstindex.html



Currently about half of new site-built houses in the U.S. are built by production building companies, and the percentage is expected to continue to grow. According to the Department of Energy and the NAHB (National Association of Homebuilders), out of a total of 2,415,000 housing units built in 2002, 44.8% were "stick-built production units" and 6.7% were mobile homes.[12] In 2001 there were 7,000 production homebuilding companies, compared to 90 mobile home, 200 modular, and 3,500 panelized housing manufacturers. Each year, 80% of all housing units completed are built by NAHB members. Thirty-two percent (32%) of homes built in 2002 were sold by the top 400 builders, 14% were sold by the top 100 building companies, and 6.7% of new residential units were built and sold by the five largest homebuilding companies: D.R. Horton, Pulte Homes, Lennar Homes, Centex Corporation, and KB Home (U.S. DOE 2003).

A 2002 report titled *The Impending Consolidation of the Homebuilding Industry* noted that the top 100 homebuilding companies in the U.S. built 24% of new homes in 1997, and that portion grew to 37% of new homes in 2000. The study also predicted that the top 100 homebuilders would account for 50% of the new home market by 2004 (which has happened), and that by 2011 "the top 20 builders alone could produce more than 75% of all U.S. homes" (JLC 2002b). Clearly, more new homes are being built by production homebuilding companies, whose success

[12] Of new mobile homes, 59% were shipped to the South, 20% to the Midwest, 15% to the West, and 6% to the Northeast

depends on minimizing their costs of construction and maximizing their volume of sales (Roberson et al 1998).

6.4 Ventilation Costs

Building scientists agree that it costs less to condition and ventilate a tight house than to condition a leaky one; i.e., the cost of heating and cooling a house with excess infiltration exceeds the cost of conditioning *and mechanically ventilating* a house with low infiltration (Feustel et al 1986, ASHRAE 1989, Sherman & Matson 1997). Building tightness improves ventilation efficiency the same way it improves heating and cooling efficiency—by isolating indoor air from outdoor air—which not only makes it easier and cheaper to condition indoor air, but ultimately makes it possible to control the rate of outdoor air supply. The purpose of residential mechanical ventilation in general, and standards in particular, is to balance the needs for indoor air quality and energy-efficiency by providing enough outdoor air for good indoor air quality while limiting excess outdoor air and its conditioning costs.

The cost of a mechanical ventilation system can be divided into installation costs and operating costs. Installation costs include capital costs for the fan(s), ductwork, and controls, and labor to install them. Operating costs include electricity required to operate the fan(s), energy required to condition outdoor air introduced by the fan(s),[13] and the capital and labor costs of repair and maintenance (e.g., filter cleaning, replacement). Relative costs of various types of ventilation systems are discussed in **Types of Ventilation Systems**, and in detail by Roberson et al (1998)**.**

In most new houses, the person who selects the mechanical ventilation system (if any) is not the one(s) who will pay the operating costs. Especially in production homes, there is little incentive for builders to use anything other than the system with the lowest installation cost. That would be single-port exhaust ventilation, which costs $50–100 for upgrading a noisy local (bath) exhaust fan to a slightly larger and more efficient exhaust fan designed to operate continuously and quietly; assuming the same quality of installation, it requires no additional controls, ductwork, skill or time.

Of course, home builders and owners should not have to pay the cost of installing or operating a mechanical ventilation system if one is not needed. Among new U.S. houses, clear exceptions to this need are (a) homes in climates so mild that heating and air-conditioning are seldom needed, so windows can be open most of the time, or (b) houses that are so leaky that when they are closed up (for whatever reason) infiltration alone provides a minimum ventilation rate, even in mild weather. Part of NAHB's argument against Standard 62.2 is that many homes are in one of these categories.

If and when homeowners *do* pay the cost of installing and operating a whole-house mechanical ventilation system, then that system should provide adequate ventilation as intended. The problem identified and addressed in this thesis is that most new U.S. houses are tight enough to need mechanical ventilation but not tight enough for small (≤100 cfm) fans to control air exchange. Standard 62.2 ignores the impact of building tightness and undersizes residential ventilation fans. As a result, for any given climate, leakier houses (which are ventilated primarily by infiltration) will have better indoor air quality and higher conditioning costs, while houses that are tight enough to be ventilated primarily by the ventilation fan will have lower conditioning costs but will not receive adequate ventilation. In other words, as currently written, the Standard does not

[13] Ventilation system operating costs do *not* include the cost of energy required to condition outdoor air that is introduced by infiltration in the absence or non-operation of the ventilation fan(s).

meet its objective. To understand why, it is first necessary to understand the basics of building airtightness, infiltration, mechanical fans, and how the interaction of these factors affects air exchange rates.

6.5 Airtightness of New U.S. Houses

To determine whether a house needs a mechanical ventilation system, one first needs to estimate how much infiltration it receives, and the extent that infiltration varies throughout a typical year. The amount of ventilation provided by infiltration (i.e., uncontrolled natural ventilation) is highly variable, and basically depends on two factors: a) the airtightness or leakage area of a building, which seldom changes, and b) the driving forces of weather, which can vary continuously. Estimating infiltration rates is complex, but starts with quantifying the tightness of a building.

6.5.1 Blower-Door Measurements: CFM50 and ACH50

Airtightness of buildings in general and houses in particular is usually measured by a process called a blower-door or fan pressurization test, originally developed in Sweden in the 1970s (Kronvall 1978), introduced to the U.S. through Princeton University (Blomsterberg & Harrje 1979), and formalized into ASTM[14] Standard E 779 in 1981 (ASTM 1999). It involves using a large door-mounted fan to pressurize and/or depressurize a house whose exterior openings (windows, doors, flues, etc) are closed and whose interior doors are open so, in effect, the building is a single zone. The flow of the blower or fan (in cubic feet/minute, or cfm) is varied and measured at intervals of 5-10 pascals indoor-outdoor pressure difference, over the range of 10-60 pascals.[15] Test results include the fan flow measured at a pressure difference of 50 pascals (0.20 inches w.g.), or CFM50.

CFM50 is the result of blower–door testing an individual house, but it cannot be used to compare the tightness of different houses unless it is 'normalized' by the volume of each house. Therefore, CFM50 is multiplied by 60 (minutes/hour) and divided by the volume of the house in cubic feet (equal to one "air change") to yield a value called 'air changes per hour at 50 pascals,' or ACH50:

$$\frac{\text{ft}^3}{\text{min}} @50\text{ Pa}\left(\frac{60\text{ min}}{\text{hour}}\right)\left(\frac{\text{air change}}{\text{ft}^3}\right)=\left(\frac{\text{air changes}}{\text{hour}}\right)@50\text{ Pa} \qquad (2)$$

For example, let's say a house with 2,000 ft^2 floor area and 8 ft high ceilings measures 2,800 cfm at 50 pascals de/pressurization during a blower-door test. The house volume is 16,000 ft^3 (2,000 ft^2 area x 8 ft ceiling height); this is also the volume of one 'air change.' To calculate ACH50:

$$\frac{2800\text{ ft}^3}{\text{min}} @50\text{ Pa}\left(60\frac{\text{min}}{\text{hr}}\right)\frac{\text{air change}}{16{,}000\text{ ft}^3} = 10.5\frac{AC}{hr}@50\text{ Pa} = 10.5\text{ ACH50}$$

Metric example: The same house has a floor area of 185.8 m^2 and a ceiling height of 2.44 m, for a volume of 453 m^3. The blower-door fan moves 4754 m^3/hr when the pressure difference across the building envelope is 50 pascals. To determine ACH50:

$$\frac{4754\text{ m}^3}{hour} @50Pa\left(\frac{\text{air change}}{453\text{ m}^3}\right)= 10.5\frac{AC}{hr}@50Pa = 10.5\text{ ACH50}$$

[14] American Society for Testing and Materials

[15] Pascals is a metric unit of pressure; 10 pascals equals 0.04 inches water gauge, 50 pascals = 0.20 in. w.g.; 3 pascals, which can be enough to backdraft chimneys and fireplaces, has been described as a "gnat fart."

Because ACH50 is normalized by building volume, ACH50 values are used to evaluate relative tightness among houses; the lower the ACH50 (the fewer air changes/hour), the tighter the house. ACH50 is widely used for some purposes, but it doesn't help us predict how many air changes the house will experience at the much lower pressure differences at which infiltration actually occurs. To do that, mathematical models are used to convert CFM50 and ACH50 into other useful values. The most widely used model in the U.S. is the LBL infiltration model, which was developed about 1980 by researchers trying to find a predictable correlation between blower-door measurements of building airtightness and tracer gas measurements of building infiltration (Blomsterberg & Harrje 1979, Blomsterberg et al 1979, Peterson 1979, Nylund 1980, Sherman & Grimsrud 1980).

6.5.2 Equivalent (or Effective) Leakage Area

Besides CFM50 and ACH50, a blower-door test yields two calculated values that characterize the relationship between air flow through a building envelope and the pressure difference across it; the power law equation approximates this relationship for an entire building (ASTM 1999):

$$Q = C\,(\Delta P)^{n} \tag{3}$$

where ΔP = the pressure across the envelope, in Pa (or in. w.g.)
Q = air flow through the blower-door at ΔP, in cfm (or m^3/h)
C = the power law **coefficient**,[16] in cfm/Pa (or (m^3/h)/Pa)
n = the power law **exponent**, dimensionless

Coefficient C relates to leakage area and exponent n relates to the building's resistance to airflow. They are derived from the blower door test by plotting the ΔP vs Q results, then fitting to the data the power law equation. Exponent n collectively represents the three-dimensional geometry (height, width, depth) of the building's holes; it is a dimensionless number between 0.5 (for orifice or turbulent flow) and 1.0 (for laminar or viscous flow). The larger and shallower the openings, the less resistance they pose to airflow and the closer n is to 0.5; the narrower and deeper the openings, the more resistance they pose to airflow, and the closer n is to 1.0. When n has not been calculated, it is usually assumed to be 0.65. The power law equation is discussed more fully in many books and papers, including Liddament (1996) and ASHRAE Fundamentals (1989, 1993, 1997, 2001).

The next step in characterizing building airtightness is to calculate the final result of the blower-door test—Equivalent (or Effective) Leakage Area (ELA). ELA was originally developed as a key parameter in the LBL Infiltration Model (discussed below), and is now specified by ASTM E 779 (1999). Automated blower-door test equipment calculate this result automatically:

$$ELA = C\sqrt{\rho/2}\,(\Delta P_r)^{n-0.5} \tag{4}$$

where ELA = equivalent leakage area, in ft^2 (or m^2)
C = coefficient from the power law, corrected to standard conditions (sea level, 68 °F or 20 °C)
ρ = the density of outdoor air, 0.075 lb/ft^3 (or 1.2 kg/m^3)
ΔP_r = the reference pressure = 4 Pa (or 0.016 in. w.g.) in the U.S.
n = the dimensionless exponent from the power law equation

[16] These parameters are called 'air leakage' or 'flow' coefficient, and 'pressure' or 'flow' exponent; to avoid further confusion, this paper refers to them as 'power law coefficient' and 'power law exponent.'

The reference pressure is important because, as the flow changes with pressure, so does the ELA.

Another version of the ELA calculation is provided in ASHRAE Fundamentals 1989–2001:

$$ELA = C_6 Q_r \sqrt{\frac{\rho}{2\Delta P_r}} \div C_D \quad (5)$$

where C_6 = a unit conversion factor = 0.186
Q_r = the predicted airflow rate at the reference pressure, in cfm (or m^3/h)
ΔP_r = the reference pressure = 4 Pa (or 0.016 in. w.g.) in the U.S.
C_D = the assumed discharge coefficient = 1.0 (dimensionless) in the U.S.

From ASHRAE Fundamentals 1989, Chapter 23:

> "By calculating (ELA), all the openings in the building shell are combined into an overall opening area and discharge coefficient for the building. Some users of the leakage area approach set the discharge coefficient equal to 1.0. Others set C_D = 0.61, i.e., (that of) a sharp-edged orifice. The leakage area of a building is therefore the area of an orifice (with an assumed value of C_D) that would produce the same amount of leakage as the building envelope at the reference pressure."

When calculating ELA from blower-door test results, ASTM Standard E 779 (1999) specifies a reference pressure of 4 Pa (0.016 in. w.g.) and a discharge coefficient of 1.0. The corresponding Canadian standard (CGSB 1986) uses a reference pressure of 10 Pa (0.04 in. w.g.) and discharge coefficient 0.61. ASHRAE Fundamentals (1989–2001) provides ways to convert between them.

Absent blower-door test results, building ELA can also be estimated by summing the effective leakage area of individual building components (exterior ceiling, doors, floor, walls, etc). ASHRAE Fundamentals provides tables listing "best estimate, max, and min" ELA values (at 4 Pa reference pressure) for a range of building components, based on lab and field measurements. For example, in Chapter 23 of 1989 Fundamentals, Table 3 lists the following component ELAs:

- SILL FOUNDATION–WALL, Caulked: Best estimate 0.04 in^2/ft of perimeter,
- WINDOWS, Casement, Weatherstripped: Best estimate 0.011 in^2/ft^2 of window,
- DOORS, Attic Access, Not weatherstripped: Max and Best estimate 4.6 in^2 each,

Summing of individual component ELAs is tedious because it requires counting or measurement of each component as well as judicious selection of its ELA 'multiplier.' It is mentioned because it is used to 'calibrate' the ELA of the house modeled in the **Methods** section of this thesis.

6.5.3 Normalized Leakage and Standard 119

ELA is similar to CFM50 in that they both characterize the airtightness of a specific building, and just as CFM50 is normalized to ACH50 to compare airtightness values of different buildings, ELA values must also be normalized to compare leakage areas between buildings. ASHRAE Standard 119–1988 (RA94) *Air Leakage Performance for Detached Single-Family Residential Buildings* codifies the equation for converting ELA to normalized leakage (NL), as follows:

$$NL = 1000 \frac{ELA}{A} \left[\frac{H}{H_0} \right]^{0.3} \quad (6)$$

where NL = normalized leakage, dimensionless
ELA = effective leakage area, in ft^2 (or m^2)

A = floor area of conditioned space, in ft^2 (or m^2)
H = height of the building, ft (or m)
H_0 = height of a single story, 8 ft (or 2.5 m)

To calculate NL, you need to know three things: house ELA, floor area, and building height. [17]

According to itself, ANSI/ASHRAE Standard 119 (1988) has two purposes: 1) "to establish performance requirements for air leakage of residential buildings to reduce the air infiltration load" and 2) to provide "a method to classify the airtightness of residential buildings." Standard 119 does this by defining Leakage Classes A–J according to ranges of Normalized Leakage (with Class A being the tightest, Class J the leakiest) and specifying acceptable leakage classes according to location (major city), infiltration degree-days (IDDs, including both heating and cooling), or climate. From page 5 of Standard 119:

> "Infiltration degree-days are a measure of the severity of the climate as it affects infiltration loads in much the same way that heating degree-days are a measure of the severity of the heating season as it affects conduction through the building envelope…
>
> "Heating (season) infiltration degree-days are compiled for every hour in which the dry-bulb temperature is below the (heating) base temperature… Cooling (season) infiltration degree-days are compiled for every hour in which the dry-bulb temperature is above the (cooling) base temperature *and* the enthalpy is greater than the base enthalpy."

Standard 119's Table 2 and 3 are reproduced in **Tables 3** and **4**, respectively. **Table 5** lists excerpts from Standard 119's Table 1a, which gives acceptable leakage classes for major cities.

Notice that all leakage classes (A–J) are acceptable in the mild climate of Los Angeles, while only leakage classes A–D (i.e., homes with normalized leakage < 0.28) are acceptable in Fargo ND. In the 1998 report *The Use of Blower-Door Data*, Sherman provides the following qualitative description of Standard 119's leakage classes:

> "A building of Leakage Class A is sufficiently tight that no credit can be taken for infiltration towards meeting a ventilation requirement; such a house should be considered *airtight* and all ventilation and pressure relief must be designed through the mechanical system. Classes B and C represent looser, but still quite tight construction. While infiltration may be non-negligible for energy concerns in some climates, its contribution toward ventilation will be too small to count on and there is still a ventilation system requirement. Classes D and E begin to be leaky enough that the infiltration may become a significant part of the ventilation requirement. It may be possible to meet the requirement with natural ventilation or intermittent mechanical ventilation. Leakage Classes F and G (are) sufficiently leaky that in all but sheltered and mild climates mechanical ventilation is probably not needed. Leakage Classes H and above would not be expected to require (mechanical) ventilation and usually represent opportunities for cost-effective tightening."

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[17] In this author's opinion, Standard 119's definitions of story and building height should be clearer. For example, is building height the distance from the bottom (e.g., basement) floor to the peak of the roof, or from grade to the highest ceiling? If the house has a crawlspace and/or unconditioned attic, do you measure from the bottom or top of the crawlspace; do you measure to the bottom or top of the attic? Also, the height of one story is specified as 8 ft (2.5 m), but what if the house has all 9' ceilings, or vaulted ceilings with an average height of 10 ft? Do you use the actual height, or use the specified 8' (2.5 m)? I posed these questions to Standard 119's principal author, who said it doesn't matter (how story or building height is defined) because an exponent of 0.3 is applied to the height factor (H/H_0) (Sherman 2003).

Table 3. Acceptable Leakage Class
from ASHRAE Standard 119–1988

Infiltration Degree-Days		Acceptable
deg C-day	**deg F-day**	**Classes**
< 1250	< 2250	A–J
1250–1768	2250–3182	A–I
1769–2500	3183–4500	A–H
2501–3535	4501–6364	A–G
3536–5000	6365–9000	A–F
5001–7071	9001–12728	A–E
7072–10000	12729–18000	A–D
≥ 10,000	> 18,000	A–C

Table 4. Classification of Air Leakage
From ASHRAE Standard 119–1988

Normalized Leakage	Leakage Class
< 0.10	A
0.10 – 0.139	B
0.14 – 0.199	C
0.20 – 0.279	D
0.28 – 0.399	E
0.40 – 0.569	F
0.57 – 0.799	G
0.80 – 1.129	H
1.13 – 1.599	I
≥ 1.60	J

Table 5. Acceptable Leakage Classes for Selected Cities
from ASHRAE Standard 119–1988

State	City	Acceptable Leakage Classes	State	City	Acceptable Leakage Classes
AK	Nome	A–C	MN	Minneapolis	A–E
AZ	Phoenix	A–H	NV	Las Vegas	A–H
CA	Los Angeles	A–J	CA	Oakland	A–I
FL	Miami	A–G	TX	Houston	A–G
IL	Chicago	A–F	WA	Seattle	A–G
MA	Boston	A–F	ND	Fargo	A–D

Sherman's 1998 report also offers the following simplification (which is not in Standard 119):

- that "the building will be too loose *(ed: presumably for conditioning energy-efficiency)* if NL < 2000 ÷ IDD *(Ed: in units of ° C-days)*" and correspondingly,
- "a building (complies) with the tightness standard when the (following) relationship is true: 2000 ≥ IDD x NL."

Conversions between ACH50, natural infiltration, and NL are difficult enough that rules-of-thumb developed to approximate their relationship. As with other rules-of-thumb, these are used to quickly and easily generate ball-park estimates (Sherman & Wilson 1986, ASHRAE 1988):

$$ACH_{seasonal} \approx \frac{ACH_{50}}{20} \approx NL \qquad (7)$$

According to **Equation 7**, the seasonal average infiltration rate is roughly equal to the normalized leakage, which is roughly equal to the (blower-door) measured value of ACH50 divided by ~20. Empirical evidence indicates the value of this denominator actually varies from 10 to 30 (or more), depending on the building's height, exposure, and leakage distribution, and the typical wind speed, but within the U.S. it is estimated to vary from 14 to 26 (Sherman 1987, Dubrul 1988, Meier 1994).

When dealing with normalized leakage values (as in the rest of this paper) it helps to know that normalized leakage corresponds very roughly to natural infiltration, so a house with NL=0.35 can be expected to experience infiltration of ~0.35 AC/h, if averaged over several months to a year.

6.5.4 LBNL Residential Leakage Database: New Construction

Since blower-door testing was brought to the U.S. from Sweden about 1980, people have compiled results from residential buildings and ASHRAE Fundamentals (1985–2001) has summarized them. For at least the last ten years, the largest collection of blower-door data on residential buildings has been compiled by researchers at Lawrence Berkeley National Laboratory (LBNL, formerly LBL) (Sherman & Dickerhoff 1994).

Much of the early work focused on measuring leakage in existing single- and multi-family housing, in order to prioritize and optimize weatherization efforts, which are designed to minimize energy bills and optimize thermal comfort in low-income housing. In weatherization, the question became "How tight is too tight?" and blower doors were used to gauge the extent to which a home could and should be air-sealed to improve conditioning efficiency without jeopardizing indoor air quality, and *without installing a mechanical ventilation system* (Yuill 1991, ANSI/ASHRAE 1993, Tsongas 1993, Sherman 1998).

Another principal use for blower-door test results is to apply weather data and a simplified model (e.g., the LBL Infiltration Model) to the ELA to estimate infiltration rates in order to assess both the adequacy of natural ventilation and the cost of conditioning air in existing homes ventilated by infiltration (Sherman & Matson 1997). For example (from Sherman & Matson 2002):

> "Sherman (1999) evaluated how air leakage could contribute to meeting the residential ventilation standard currently proposed by ASHRAE, and found that air leakage alone is rarely sufficient to meet minimum ventilation standards in houses having a normalized leakage less than 0.5." [18]

More recently, the LBNL Leakage Database turned its attention to the airtightness of new homes, at least in part to assess their need for mechanical ventilation, and in anticipation of Standard 62.2. In 2002, Sherman & Matson reported the NL of "new" [19] houses in the LBNL database, including houses built since 1993; many were built in utility- or government-sponsored energy-efficient residential new construction programs, the largest of which is Alaska's AKWarm. Of the approximately 8,700 new houses in the dataset, the average NL was 0.30 (Leakage Class E) with a standard deviation of 0.25, indicating a wide range of airtightness among the sample. The report also averaged the NL for different types or quality of new construction, as shown in **Table 6**. Notice the relative standard deviation of NL is lower in energy-efficient than in conventional homes, indicating that airtightness becomes more consistent when builders pay attention to it.

According to that report, there is considerable uncertainty not only in the average values of NL (as indicated by their standard deviation), but also with the individual measurements. For example, in almost all cases, the power law exponent (needed to calculate ELA) was not provided, and so was assumed to be 0.65. Also, building height and/or volume often were not provided, in which case they were calculated from floor area, using an assumed ceiling height and number of storeys.

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[18] Note that while 0.35 AC/h is the recommended minimum ventilation rate, and NL ≈ AC/h, Sherman found that an NL of 0.5 was necessary to reliably achieve a minimum of 0.35 AC/h with infiltration alone. This discrepancy is attributable to the difference between (long-term) average and effective ventilation rates. For specific examples, see the **Results** section.

[19] In Sherman's report, "new" means that the blower-door test was conducted within one year of construction, not necessarily that the homes were recently built.

Table 6. Average Leakage for Residential New Construction
(from Sherman & Matson 2002: *Air Tightness of New U.S. Houses*)

Type of New Construction	approx. no. of houses	Normalized Leakage (NL)	standard deviation	Leakage Class (from Standard 119)
Conventional	1,200	0.55	0.55	F
Energy Efficient	3,100	0.31	0.13	E
Alaska's AKWarm	4,400	0.23	0.10	D

However, the greatest source of uncertainty (which is not mentioned in that report) is that very few reported blower-door results indicate whether the measured ELA (and consequently NL) includes the leakage of the forced-air system, which (as discussed in **Types of Ventilation Systems)** can easily account for 20–30% of a home's overall leakage area. This means there is significant potential error to the NL values in LBNL's Residential Leakage Database (Sherman 2003). At best, if we knew that reported leakage values *did* include forced-air leakage, the uncertainty would lie in not knowing how much of the total leakage was in the forced-air system. Alternatively, if we knew that reported leakage values *did not* include forced-air leakage, the uncertainty would lie in not knowing how much additional leakage was in the forced-air system. As it is, we have no idea; some values probably include duct leakage, while others don't, so the uncertainty is compounded.

While blower-door test results should indicate whether or not the ELA includes duct leakage, they apparently seldom do. However, in houses with a forced-air duct system, blower-door test results will include duct leakage to outside *unless* the duct system is deliberately isolated from the rest of the house by sealing all its registers.[20] This author reasons that if testing personnel take the trouble to seal (and unseal) the forced-air registers, they are also likely to document that activity; therefore, in the absence of such documentation, that step was probably not taken, and one can reasonably assume that the ELA calculated from the blower-door test includes forced-air system leakage. If our assumption (that NL values from the LBNL Leakage Database include duct leakage) is wrong, the consequence would be a significant *underestimation* of house leakage area, in which case mechanical ventilation would result in *more* airflow than is needed, not less. This author would rather err on the side of more ventilation than to fail to provide adequate ventilation in new homes.

6.6 Estimating Infiltration from Leakage Measurements

Measuring leakage area or airtightness of buildings is a first step toward estimating infiltration. Infiltration is directly proportional to leakage area, but there is no direct means for converting from leakage area to infiltration rate, because the relationship between pressure difference and airflow across building openings is non-linear and complex. According to Liddament (1996):

> "In reality, it would be a formidable task to identify the flow characteristics, driving forces, size and location of every opening. Instead, it is necessary to introduce a number of simplifying assumptions (that) allow the main physical concepts of air flow to be represented without compromising results. It is the degree to which the flow mechanics is simplified that identifies the type of model, the detail of data needed and the range of applicability of results."

[20] In practice, forced-air system leakage can be estimated by conducting two blower-door tests, one with and one without isolating the duct system, then subtracting the former from the latter result.

Four basic types of models are used to estimate air exchange rates from building leakage measurements. In increasing order of complexity, they are:
1) rules of thumb, such as **Equation 7**,
2) simplified theoretical models, e.g. the single-zone LBL Infiltration Model, discussed below,
3) multi-zone or network models, such as COMIS and CONTAM, that use an iterative process to simultaneously solve mass-balance equations for each zone in a building, and
4) computational fluid dynamics (CFD), which models airflow among many points in each zone.

The most complex method—computational fluid dynamics—is beyond the means and scope of this thesis, but the LBL Model is summarized and a multi-zone model is described in detail here.

6.6.1 LBL Infiltration Model

In 1980 Sherman and Grimsrud introduced the LBL Infiltration Model, which was incorporated into ASHRAE Fundamentals beginning in 1981. The LBL model is explained best by its authors (Sherman 1998) or by ASHRAE Fundamentals, but I will summarize it qualitatively here. A key simplifying assumption is that each building (house) is a single well-mixed zone of uniform pressure and temperature; i.e., it assumes no restrictions to airflow, such as interior floors or walls. Another key assumption is that "envelope leaks can be treated as simple orifices whose leakage characteristics can be quantified in a single parameter"—the power law exponent (Sherman 1987). The model is used to calculate an instantaneous (or hourly) building infiltration rate, which is a product of ELA and *specific infiltration (rate)*. Specific infiltration is a function of wind speed, indoor-outdoor temperature difference, and two parameters defined as the *stack* and *wind factors*.

Stack factor is a function of outdoor drybulb temperature, building height and leakage distribution; more specifically, *R* is the fraction of total leakage area that is located in the floor and ceiling, and *X* is the difference between the fractional leakage area in the ceiling and in the floor. Wind factor is a function of building height, fractional leakage area located in the walls, two *terrain coefficients* and one *shielding coefficient*. Terrain and shielding coefficients account for the moderating affects of topographic and site features (mountains, tall buildings, nearby trees and houses) on wind as it impacts the building; in other words, they adjust measured (airport) wind speed to a given building.

6.6.2 Superposition: Combining Stack and Wind Effects

With single-zone models like the LBL infiltration model, it is relatively easy to separately calculate airflows attributable to wind and stack effects, but more difficult to account for their interaction. 'Superposition' is the term used to describe a simplified process for combining driving forces. From Sherman (1992):

> "Each…mechanism induce(s) pressures across the envelope to drive the flow, but the spatial distribution of the pressure is different for each one of them. Although these pressures are additive on a point-by-point basis, the flows induced by those pressures are not… Because the individual driving forces affect the pressure distribution, they interact and simple addition usually leads to significant overprediction. Therefore…a sub-additive superposition law will be required."

The LBL infiltration model uses the method of 'quadratic superposition' or simply 'quadrature' (**Equation 8**) to approximate the combined effect of wind and stack on infiltration.

$$Q_{ws} = \sqrt{Q_w^2 + Q_s^2} \tag{8}$$

where Q_{ws} = infiltration from both wind and stack effects, cfm
Q_w = infiltration from wind effect, cfm
Q_s = infiltration from stack effect, cfm

Equation 8 remains a cornerstone of infiltration modeling; like other simplifications, it sacrifices accuracy for ease of use. Quadrature is an accepted method for combining wind and stack effects, and with some modification it can also be used to approximate the combined effects of infiltration and mechanical ventilation, which is discussed below (ASHRAE 1985, 1989, 1993, 1997, 2001).

6.6.3 Multi-Zone Models

When single-zone models (like the LBL model) do not provide enough accuracy or detail, multi-zone or 'network' models can be used; of course, the inputs to the more accurate model must also be more accurate and detailed. According to Liddament (1996), in multi-zone models:

> "a building is represented by a series of 'zones' or 'cells' interconnected by flow paths. Each 'zone' typically represents an individual room, while flow paths represent infiltration routes or purpose provided openings. Flow equations are applied that relate the pressure difference across each flow path to the resultant air flow through the opening. Additional equations represent air flow generated by mechanical ventilation….(T)his technique represents one of the closest of approximations to the true system of ventilation and infiltration air flow."

Multi-zone models assume that temperature and pressure are uniform within each zone (or room). Every opening (including leakage sites, flues, vents, exterior and interior doors, and windows) is carefully defined according to its size, height, location, and its pressure and air flow characteristics (discharge coefficient, power law exponent). In effect, the building is represented by a set of mass (or volumetric) balance equations. When all conditions (including date, time, weather) are defined, the equations are solved simultaneously through an iterative process. From Liddament (1996):

> "The objective of the calculation technique is to evaluate each internal zone pressure. It is rarely possible to evaluate this pressure by direct calculation and, instead, it is determined by 'iteration' in which an initial arbitrary pressure is first applied. The degree of deviation from flow balance is used to predict a more accurate pressure. This process is repeated until flow balance within a specified tolerance is achieved."

With multi-zone models it is possible to evaluate the effect of fans on building air change rates; each fan (dryer exhaust, forced-air, kitchen range exhaust, bath exhaust, whole-house ventilation) can and should be precisely defined according to its flow rate, location, and operating schedule. Effects of closed interior doors can also be evaluated by assigning operating schedules to them (e.g., by assuming that bedroom doors are closed at night, but remain open during the day).

It is also possible to precisely define the overall tightness of a building. From Liddament (1996): "(T)ightness is specified in the design…and verified by (simulated blower-door) pressurisation on completion of the building. Any leakage in excess (of that specified) should be traced and rectified." Using detailed (e.g., typical meteorological year) weather data, effects of wind and temperature on building configuration, orientation, and geographical location can be evaluated.

Multi-zone airflow models are a powerful tool that enable building scientists to quickly and easily (compared to tracer gas measurement) evaluate the effects of varying conditions on building air change rates and interior airflow patterns. There are at least two public-realm multi-zone models. COMIS was developed through an international effort organized by the International Energy Agency (Feustel 1996), and CONTAM was developed by the National Institute of Standards and

Technology (NIST), ostensibly for modeling and predicting the movement of smoke in buildings. COMIS and CONTAM incorporate basically the same assumptions, equations, inputs, and results, but CONTAM is considerably easier to use (Brennan 2002, Fisk 2003, Persily 2003). This study uses CONTAM to model house airflows; the **Methods** section describes CONTAM in more detail.

Now I've summarized the means for estimating infiltration from airtightness measurements, I will briefly review the history and evolution of residential ventilation rate requirements, which should provide a better appreciation of the interaction between natural and mechanical ventilation.

6.7 History of Ventilation Requirements

Ever since people brought fire indoors, we have struggled to balance the competing needs of heating and ventilation. First came the realization that an opening in the roof, preferably over the fire, facilitated smoke removal; next, windows that were installed primarily to provide daylight were made operable for the purpose of controlling ventilation. Gradually people investigated and began to understand the qualities and quantities of air that optimized human health and comfort.

In the 1770s Lavoisier, a chemist, identified carbon dioxide (CO_2) as a component of indoor air whose concentration inversely correlates with perceived air quality. Since then, the minimum rate of outdoor air flow needed to dilute CO_2 to within acceptable limits has been much debated. About 1830 a mining engineer named Tredgold was the first to propose a minimum standard of 4 cfm outdoor air per person, which did not account for the concentration of CO_2 present in room air. In the 1890s, concern about spread of disease, particularly tuberculosis, led Billings, a physician, to propose a minimum rate of 30 cfm—and preferably 60 cfm—per person. This minimum rate was proposed by ASHVE [21] in 1895, adopted in 1914, and by 1925 had been incorporated by 22 states; only the recent availability of electricity to operate fans made this ventilation rate possible. Confusion arose, however, over how much of the '30 cfm per person' should come from outdoors.

Ironically, the finding in the early 1900s that tubercular children were better off outdoors than in mechanically ventilated schools led to a preference for open windows that prevailed for 50 years. However, increasing pollution of outdoor air in cities, along with the advent of air-conditioning (i.e., compressor-based cooling, which allowed deeper floor plans that required electric lighting, which in turn required more cooling), eventually swung the pendulum back in favor of mechanical ventilation in general, and forced-air distribution systems in particular, at least in commercial buildings. Meanwhile, experiments by Yaglou and others concluded that only half the minimum ventilation standard (30 cfm/person)—or 15 cfm person—needed to be 100% outdoor air; the remainder of 'ventilation airflow' could be recirculated indoor air (Janssen 1994, Addington 2001).

6.7.1 ASHRAE Ventilation Standard 62

In 1973 ASHRAE published its first ventilation standard, *ASHRAE 62–1973 Standards for Natural and Mechanical Ventilation*, which recognized that ventilation requirements vary according to the type and use of space; of 271 spaces identified, 10 were residential. It prescribed an absolute minimum of 5 cfm outdoor air per occupant, with higher minimums for certain types of buildings.

[21] American Society of Heating and Ventilating Engineers, a precursor of ASHRAE.

When Standard 62 was first revised in 1975, it maintained its prescriptive approach to ventilation, but concerns about energy-efficiency following the Arab Oil Embargo and ensuing energy crisis led ASHRAE to reduce the minimum ventilation rate to 5 cfm per person in all buildings.

When next revised in 1981, concerns about the health effects of second-hand or environmental tobacco smoke (ETS) led ASHRAE to recommend a dual minimum standard of 5 cfm per person in non-smoking and 25 cfm per person in smoking environments; *Standard 62–1981 Ventilation for Acceptable Indoor Air Quality* also recommended a limit on the concentration of formaldehyde in indoor air. Of 65 types of space addressed, 7 were residential. Standard 62-1981 recognized there is both a health and comfort component to indoor air quality, and introduced a performance as well as a prescriptive approach to ensuring indoor air quality. However, opposition from the tobacco and formaldehyde industries prevented Standard 62–1981 from being adopted by the American National Standards Institute (ANSI), and therefore by building codes and the public (Addington 2001, Janssen 1994, Stanke 1999).

6.7.1.1 Standard 62–1989

The pendulum of ‘energy-efficiency vs indoor air quality’ swung back towards indoor air quality in the early 1980s when experimental work by Ole Fanger and others concluded that a minimum of 15 cfm outdoor air per person is needed to make occupant-generated odors acceptable to 80% of outside “visitors” who are not acclimated to the indoor air. Combined with the proliferation of non-occupant-generated indoor pollutants, this resulted in ASHRAE *Standard 62–1989: Ventilation for Acceptable Indoor Air Quality* raising the minimum ventilation rate in all buildings to 15 cfm per person. It recognized 82 types of commercial and 5 types of residential space, but eliminated industrial spaces, which were left to OSHA[22] regulation. Standard 62-1989 maintained the option of demonstrating compliance via the prescriptive ‘ventilation rate’ or the performance-based ‘indoor air quality’ procedure. It also introduced the concepts of ‘air exchange effectiveness’ and ‘ventilation system efficiency,’ and eliminated separate requirements for smoking environments (Addington 2001, Janssen 1994, Stanke 1999).

For residential buildings, Standard 62–1989 specified a minimum of 0.35 AC/h or 15 cfm/person, whichever was greater. These dual (volume- and occupant-based) specifications acknowledged that air pollution in residences is often dominated by building-source rather than occupant-source pollutants, at least in part because residences tend to have fewer people per unit area than other buildings. Unless known to be higher, the number of occupants was assumed to be one person for each bedroom, and an additional person in the master bedroom. In spite of such specificity, Standard 62–1989 did not say whether or when residential ventilation requirements could be met by infiltration alone or a combination of natural and mechanical ventilation, Many practitioners considered 62–1989 too ambiguous to ascertain compliance, at least in homes (Sherman & Matson 1997). However, it was approved by ANSI and adopted by enough building codes to become “accepted as the ‘standard of care’ in most legal proceedings involving IAQ” (Wheeler 1999).

6.7.1.2 Standard 62–2001

In 1997 ASHRAE decided that instead of periodic revision, Standard 62 would thenceforth be updated through as-needed development of addenda, or ‘continuous maintenance,’ during which ASHRAE became increasingly aware of the fundamental differences between the ventilation issues of residential and non-residential buildings. Eventually, ASHRAE decided that Standard

[22] Occupational Safety and Health Administration

62 should focus on non-residential buildings, and that low-rise residential buildings needed their own separate but related ventilation standard, to be called Standard 62.2 (Sherman 1999, Wheeler 1999). Yet development of Standard 62.2 was a long and difficult process, and adoption was not assured; meanwhile, ASHRAE Standard 62 remained the standard for ventilation of residential buildings.

As published in 2001 (ANSI/ASHRAE), Standard 62 requires the same residential ventilation rate that it has since 1989: “except where other applicable standards and requirements dictate *larger* amounts (italics added)… 0.35 air changes per hour but not less than 15 cfm (7.5 L/s) per person.” Building scientists understand that for residential buildings, the ’15 cfm/person’ rate prevails “when occupants are the primary source of pollutants (e.g., carbon dioxide, body odor). If the building itself produces more pollutants (e.g., formaldehyde), as is more often the case for residential structures, a criterion based on air changes is more appropriate” (Palmiter et al 1990).

6.7.2 International Residential Ventilation Standards and Practice

The purpose of this section is to provide a basis of comparison between U.S. standards and those of other countries that have already tackled the issue of ensuring outdoor air supply to homes. This list is not intended to be exhaustive or complete, but descriptive of how (and how well) other jurisdictions perceive and address the relationship between residential building airtightness, ventilation rates, and the performance of mechanical ventilation systems. Because there are many ways to specify airtightness and ventilation, it can be difficult to compare standards between countries, but where possible, I have converted airtightness to units of ACH50 (air changes per hour at 50 pascals) and expressed ventilation rates in terms of:

- AC/h at normal pressures (when rates are based on building volume), and/or
- cfm (and liters/second) per person (when rates are based on occupancy).

In Europe, residential mechanical ventilation evolved separately from home heating systems, which are predominantly hydronic (c.f. forced-air), and central air-conditioning, which is uncommon. Free of the temptation to adapt existing forced-air conditioning systems to meet ventilation needs, Europeans designed ventilation systems with as much appropriately-sized ductwork as necessary to adequately distribute outdoor air among rooms. Most mechanical ventilation systems are either balanced heat-recovery or multi-port exhaust, depending on the severity of the climate, and budget.

6.7.2.1 Europe

Residential mechanical ventilation was first developed in the cold climate of Scandinavia, where building codes continue to focus on building airtightness and heat recovery in order to maximize ventilation system efficiency and minimize the costs of conditioning ventilation air. In the 1980s, Sweden specified a minimum airtightness rate for new single-family homes of ≤ 3.0 ACH50; for other low-rise residential buildings, it specified an airtightness of ≤ 2.0 ACH50. These home tightness levels are summarized in **Table 7**, along with those of Norway (Liddament 1986).

Table 7. Minimum Airtightness of Homes in Norway and Sweden, in AC/h at 50 pascals
Source: Liddament 1986, Colthorpe 1990

Type of residential building	Sweden	Norway
Single-family dwellings (detached, semi-detached, and terraced)	≤ 3.0	≤ 4.0
Other residential buildings of up to 2 stories	≤ 2.0	≤ 3.0
Residential buildings of 3 or more stories	≤ 1.0	≤ 1.5

In 1988 Sweden changed its specification of airtightness limits, which for dwellings is now ≤ 3.0 m^2/m^3 h, where m^2 is the area of the building envelope (walls, floor, ceiling)—not the floor area. Virtually all Swedish homes have a 'domestic' ventilation system, either passive or mechanical. Mechanical systems are either balanced or exhaust ('extract'), and heat recovery is cost-effective. Balanced systems usually include a heat exchanger, and exhaust systems often incorporate an air-to-water heat pump that transfers heat from outgoing air to the domestic hot water supply. Because houses are so tight, passive vents are a requisite part of any exhaust ventilation system. Sweden was the first to recognize that ventilation efficiency depends on building airtightness, and also that airtightness is more critical to the performance of balanced than unbalanced systems. In Sweden the recommended ventilation rate for homes is a minimum of 0.35 L/s per m^2 floor area, which is about 0.5 AC/h for a 1500 ft^2 home (Liddament 1986, Colthorpe 1990, Limb 1994, Bower 1995).

The Finnish Building Code recommends a residential ventilation rate of 0.5 AC/h or 4 L/s (8 cfm) per person. As of 1993, approximately 75% of new detached houses in Finland had a mechanical ventilation system; of those, just over two-thirds (~70%) were balanced systems, just under one-third (~30%) were exhaust ventilation systems, and the portion of balanced ventilation systems that incorporate heat recovery had been growing steadily (Colthorpe 1990, Kauppinen et al 1993).

Germany specifies a minimum ventilation rate of 1.0 AC/h for living rooms (Colthorpe 1990).

In the relatively mild climate of the United Kingdom, standards regarding residential ventilation are lackadaisical compared to other developed countries. Britain basically assumes that homes will be ventilated by infiltration and/or that people will open their windows as necessary. Tightness standards exist for some building components (e.g., windows) but not for buildings. **Table 8** shows the residential ventilation rates recommended by British standards and CIBSE. [23]

Table 8. Recommended Ventilation Rates for Homes in the U.K.

(Note: These L/s and cfm values can be translated to AC/h if building volume is known.)

Dwelling Type	Minimum Rate, per person	Recommended Rate, per person
Average	8 L/s (17 cfm)	12 L/s (25 cfm)
Luxury	12 L/s (25 cfm	18 L/s (38 cfm)

Although not required, the use of continuous mechanical ventilation—either multi-port exhaust or balanced systems—is growing in the UK, and while heat-recovery is not cost-effective in their climate, it is often included for its other advantages, including air filtration and better distribution (Liddament 1986, Limb 1994). The Building Research Establishment (BRE 1994) offers the following guidelines, among others, for mechanical ventilation (MV) of homes:

> "For optimum economic operation of the MV system, the dwelling must be as airtight as practicable. This means a background infiltration rate of about 0.2 ach…Generally speaking, a dwelling with a mean natural infiltration rate of 0.2 ach will have an air leakage rate, at an applied pressure of 50 pascals, of about 4 ach… With an air leakage rate of 4 ach at 50 pascals, it is probably sufficient to rely on structural air leakage. In more airtight buildings, small openings, such as trickle ventilators, are needed in each room… These openings are unnecessary with (balanced) systems… A whole-house ventilation rate of 0.5 ach, with some additional extract ventilation in the wet rooms during moisture production, will generally keep water vapour and other pollutant concentrations below accepted maxima."

[23] Chartered Institute of Building Services Engineers

In short, while residential mechanical ventilation is not required in the UK, it is understood.

Switzerland emphasizes natural ventilation and occupant control of and responsibility for window operation. To that end, it recommends a minimum ventilation (i.e., infiltration) rate of ≥ 0.3 AC/h for all buildings during normal weather when windows and other exterior openings are closed. Regarding airtightness, the Swiss standard makes a notable exception for buildings with *balanced* mechanical ventilation systems, which must have an airtightness of ≤ 1.0 ACH50—in other words, extremely tight. Beyond the minimum 'natural' ventilation rate of 0.3 AC/h, Switzerland recommends ventilation rates of 0.4 AC/h for single-family housing and 0.6 AC/h for multi-family housing, but designers are free and expected to find their own method of providing it. Homes with exhaust ventilation are required to have passive vents installed as part of the system (Liddament 1986, Colthorpe 1990, Limb 1994).

Similar to Switzerland, Belgium recommends that homes with balanced *heat recovery* ventilation systems have an airtightness of ≤ 1.0 ACH50; however, if a balanced ventilation system does not incorporate heat recovery, the tightness recommendation is relaxed to ≤ 3.0 ACH50 (Limb 1994).

In France, mechanical ventilation systems have been common in homes since the 1960s. Since 1969, France has required that new homes receive a minimum of 1.0 AC/h, on a continuous basis. More specifically, it requires outdoor air to be introduced to all habitable rooms (living rooms and bedrooms), and that indoor air be exhausted from all service rooms (bathrooms and kitchens). France does not specify minimum or maximum building airtightness, but requires that ventilation heat loss be calculated. As of 1993, roughly 10% of French homes (including multi-family) had natural or passive ventilation; the other 90% had mechanical systems. Among French houses with mechanical ventilation, balanced systems are much less common than exhaust systems, partly because the weather is relatively mild (c.f. Scandinavia), but also because the French understand that many residential buildings are not tight enough for balanced ventilation to be effective. In France, exhaust systems are either multi-port or a type called "demand controlled ventilation" that regulates exhaust airflow according to relative indoor humidity,[24] which is directly correlated with occupancy; the lower the humidity (or occupancy), the lower the ventilation rate, and its corresponding heat loss. (Liddament 1986, Colthorpe 1990, Riberon et al 1993, Limb 1994).

6.7.2.2 Japan

Japan's Building Standards Law (revised effective 2003), recommends that residences receive at least 0.50 AC/h (Sawachi 1998). The New Generation Energy Conservation Standard (updated 1999) sets these airtightness guidelines for new homes: ≤ 2.0 cm^2 aggregated opening area per m^2 surface (envelope) area in cold climates, ≤ 5.0 cm^2/m^2 in moderate climates (Motegi 2004).

6.7.2.3 New Zealand

In New Zealand's relatively mild climate, residential ventilation focuses on moisture control. New Zealand Standard (NZS) 4303:1990 *Ventilation for Indoor Air Quality*, is adapted from ASHRAE Standard 62–1989. Like 62–1989, the NZ standard does not require mechanical ventilation of homes, but recommends living areas, including bedrooms, receive at least 0.35 AC/h or 7.5 L/s (15 cfm) per person. It also recommends kitchens receive a rate of 50 L/s (100 cfm) intermittent or 12 L/s (24 cfm) continuous, and bathrooms receive a rate of 25 L/s intermittent or 10 L/s (20 cfm) continuous. According to a NZ building scientist, this yields a

[24] "Demand controlled ventilation" can also refer to regulation of outdoor air flow according to CO_2 levels.

space-weighted average ventilation rate of 0.5 AC/h for the typical New Zealand home (Bassett 1992, Limb 1994, Bassett 2001).

6.7.2.4 Canada

In 1989 Canada introduced a preliminary standard requiring mechanical ventilation in homes (CSA 1989), and in 1995 a formal version became part of Canada's National Building Code (CAN/CSA 1995, CMHC 1996). Canada's standard requires houses to have mechanical ventilation. It does not include airtightness requirements but specifies minimum ventilation rates *for each habitable room*: ≥ 10 L/s for basements and master bedrooms, and ≥ 5 L/s each for other rooms (bedrooms, kitchen, living room). For most houses, this adds up to ≥ 0.3 AC/h (Hayson & Reardon 1998).

Canada leads the world by specifying mechanical ventilation rates for each habitable room. As this usually requires ductwork, houses with forced-air conditioning systems usually use those large ducts to distribute ventilation air as well, as discussed in **Forced Air Supply Ventilation**. Yet even Canada has problems using forced-air systems for ventilation. Energy Design Update (EDU 2004) reports that a CMHC[25] study of eight new houses found that duct leakage significantly impaired the ability of forced-air systems to actually deliver the design (minimum) ventilation rate. In a more extensive study of ventilation systems in Canadian houses *without* forced-air heating, Canadian scientists compared the ability of several exhaust-only and one "minimal ducted supply" system (i.e., multi-port supply ventilation) to distribute ventilation air in a house. They found that the "minimal ducted supply system (balanced by exhaust to avoid condensation within walls) provided the best outdoor air distribution to all the habitable rooms" (Reardon & Shaw 1997).

Canada limits depressurization to 5 pascals if natural-draft flues or chimneys are present, otherwise 10 pascals; the lower value is to prevent backdrafting and the upper value to limit intrusion of radon. Pressurization is also limited to 10 Pa to minimize "interstitial condensation." Canada's standard recommends sealed-combustion equipment and encourages balanced ventilation with and without heat recovery (Liddament 1986, Colthorpe 1990, Limb 1994, Hayson & Reardon 1998).

The Canadian procedure for measuring airtightness with a blower-door is the same as ASTM's, except Canada specifies a reference pressure of 10 Pa (instead of 4 Pa) and a discharge coefficient of 0.6 (instead of 1.0) (CGSB 1986, ASTM 1999). Results from a 1989 survey of almost 200 new Canadian homes yielded an average tightness of 3.44 ACH50 (Hamlin 1991), or an NL of ~ 0.17.

Canadian single family homes constructed according to HUDAC[26] or the voluntary R–2000 Energy Efficient Home Program specifications are required to have airtightness of ≤ 1.5 ACH50. Mechanical ventilation is required in R–2000 homes; most have balanced HRV systems, but exhaust systems are allowed as long as they don't depressurize the house to more than 10 Pa during continuous operation or more than 20 Pa during intermittent operation. Depressurization limits are imposed primarily to limit radon intrusion; only sealed or forced-draft combustion appliances are allowed, except fireplaces and woodstoves, which must have tight-fitting doors and dedicated combustion air supply. Initially, R–2000 required a mechanical airflow rate of 0.5 AC/h, but later became more specific in terms of ventilation requirements in each room (Piersol & Riley 1987).

[25] Canada Mortgage and Housing Corporation
[26] Housing and Urban Development Association of Canada

Table 9 summarizes these countries' practices regarding home airtightness and ventilation.

Table 9. Summary of International Residential Airtightness and Ventilation Standards

Country	Building Airtightness	Residential Ventilation Rate
Belgium	≤ 1.0 ACH50 recommended with balanced HRV, otherwise ≤ 3.0 ACH50	≥ 1.0 L/s per m2 floor area, plus exhaust in bathrooms & kitchen
Canada	≤ 1.5 ACH50 required for new HUDAC and R-2000 homes	requires 5-10 L/sec mechanical ventilation be distributed to/from individual rooms; typically amounts to ~ 0.3 AC/h
Finland	no requirement	≥ 0.5 AC/h recommended
France	no requirement for tightness; requires calculation of ventilation heat loss	≥ 1.0 AC/h continuous required; must be supplied to living/bedrooms, exhausted from kitchen & bathrooms
Japan	aggregated leakage per envelope area: ≤ 2.0 cm2/m2 (cold climate) ≤ 5.0 cm2/m2 (moderate climate)	≥ 0.5 AC/h recommended
New Zealand	no requirement	≥ 0.35 AC/h or 15 cfm (7.5 L/s) per person recommended
Norway	≤ 4.0 ACH50 required for new single-family detached homes; ≤ 3.0 ACH50 for other homes	supply openings and exhaust rates specified by room type
Sweden	≤ 3.0 ACH50 required for single-family; ≤ 2.0 ACH50 required for other homes	≥ 0.35 L/s required per m2 floor; must be continuous; ~0.5 AC/h for 2400 ft2 home
Switzerland	≤ 1.0 ACH50 required with balanced ventilation systems; 2.0-3.0 ACH50 recommended for exhaust ventilation	recommended: ≥ 0.40 AC/h in single-family homes, ≥ 0.60 AC/h in multi-family homes
United Kingdom	when mechanical ventilation is present, recommendation is for homes to be as tight as practicable	recommended: ≥ 8 L/s (17 cfm) per person ≥ 1.0 AC/h in living and bedrooms, ≥ 3.0 AC/h in kitchen & bathrooms
USA	recommendations per ASHRAE Std 136, but no requirement	recommended: ≥0.35 AC/h or 15 cfm/person, whichever is greater

The main points to be taken from this discussion of home airtightness and ventilation standards around the developed world are the following:

a) Among countries that specify minimum residential ventilation rates, all recommend at least 0.35 AC/h except Canada, which specifies minimum rates for each room.
b) Several countries recommend a minimum home ventilation rate of at least 0.50 AC/h, while the UK recommends ≥ 1.0 AC/h and France requires ≥ 1.0 AC/h—continuous.
c) Most countries recognize that airtightness is critical to mechanical ventilation.
d) Tightness is even more important for balanced than for exhaust ventilation systems.

6.7.3 State Residential Ventilation Standards

Not surprisingly, states along the Canadian border were the first in the U.S. to develop standards for mechanical ventilation of homes, with varying degrees of success. Again, these descriptions do not attempt to describe each code in comprehensive detail, but rather to focus on how (and how well) each jurisdiction addresses the relationship between airtightness and ventilation performance.

6.7.3.1 Washington

In the Pacific Northwest (Idaho, Oregon, Washington) most buildings, including homes, are heated with electricity produced by hydro–electric power plants. Although the climate in much of the region is not particularly harsh, the need to conserve electricity has motivated utilities, particularly the Bonneville Power Administration (BPA), and state governments to undertake some of the most progressive building energy-efficiency programs in the country, including tightening of houses to improve the efficiency of space heating (and mechanical cooling, if any). These have been so successful that in 1991 Washington State instituted its Ventilation and Indoor Air Quality (VIAQ) Code, which was ostensibly designed to ensure adequate outdoor air supply in all buildings. It required each dwelling unit in low-rise (up to 4-story) residential buildings to have a "whole house ventilation system" capable of providing at least 0.35 AC/h or 15 cfm/person, in accordance with ASHRAE Standard 62–1989. It also required that systems "be designed to limit ventilation to a level no greater than 0.5 AC/h under normal operating conditions," except for smaller dwelling units (≤ 1,400 ft^2), which could receive up to 0.65 AC/h (WA State Energy Office 1993).

Unfortunately, and in spite of good intentions, Washington's VIAQ Code was so poorly written that even the most conscientious contractors could not make any practical sense of it. It failed to define, much less describe the three basic types of ventilation systems (balanced, supply, exhaust) or to distinguish their basic components. For example, it prescribed "individual room outdoor air inlets…which provide 10 cfm at 10 pascals" without explaining that they are to be used with exhaust, but not supply or balanced systems. Also Washington, like most of the rest of the U.S., failed to account for or even acknowledge the effect of house tightness on mechanical ventilation performance. After years of confusion and complaints, a field evaluation study of the VIAQ Code confirmed that its goals were not being met and that it should at least be rewritten, if not overhauled (Devine 1999, EDU 1999c, EDU 200b.2).

6.7.3.2 Minnesota

In 1991, Minnesota—the state with one of the harshest climates in the U.S. outside Alaska—legislated that its state energy code should meet or exceed any other energy code in the country. Recognizing that building airtightness is requisite for space heating efficiency, and that new homes would require mechanical ventilation systems that must be both efficient and effective, the Residential Ventilation Standards Task Force was organized to develop an appropriate standard. The Task Force adopted the minimum residential ventilation requirements of Standard 62–1989, but specified that the principal or 'people' ventilation rate of 15 cfm/person be continuous, while the supplemental ventilation rate (the remainder needed to meet 0.35 AC/h) could be intermittent.

The Task Force and resulting standard focused on three key components of safe, effective and efficient ventilation: (1) airtightening, (2) continuous mechanical ventilation, and (3) setting depressurization limits according to the type of combustion equipment and exhaust fans present (including clothes dryers and kitchen range hoods) to prevent backdrafting and limit radon intrusion. Because positive indoor pressure can push moist indoor air into exterior walls, where in cold climates it might condense, accumulate, and lead to structural damage, pressurization was limited to 5 Pa, which effectively excludes supply ventilation systems (which, to be effective, should pressurize a house by at least 5 Pa). Though not explicitly excluded, use of exhaust ventilation systems was severely restricted because the standard also limited depressurization to 2 or 5 pascals if the house has an atmospherically-vented water heater or furnace, respectively.

In 2000, as part of its new energy code, Minnesota became the second state in the U.S. (after WA) to require new homes to have a mechanical ventilation system. Minnesota's standard was well conceived, planned, vetted, written, and implemented; they sought and received input from as many industry experts, practitioners, and stakeholders as possible, including many in Canada. Unlike Washington, Minnesota required residential ventilation systems to be continuous; it also understood and anticipated the interaction of building tightness, fan size and direction, and any depressurization hazards. The MN standard provided a performance and several prescriptive paths to compliance, but required all systems to be performance-tested after installation to verify de/pressurization limits, house ventilation rates, and distribution of outdoor air to each living area. Minnesota's code is a tremendous improvement over Washington's, and it wisely guided builders towards balanced heat-recovery ventilation systems, which are most appropriate for that climate, and sealed combustion appliances, which are not susceptible to backdrafting by depressurization (RVSTF 1995, EDU 1998, EDU 1999b, Minnesota 2000, Nelson 2000, Bolsta 2001).

6.7.3.3 Vermont

In 1995 Vermont Governor Howard Dean created the Task Force on Energy Efficiency Standards for New Residential Construction, whose purpose was to develop the first statewide energy code. The resulting Vermont Energy Code, officially Residential Building Energy Standards (RBES), was enacted in 1997 and applied to all homes built after June 1998. The first version of the code did not require mechanical ventilation, but when the first revision of the code was completed in 2003, Vermont became the third state to require mechanical ventilation systems in new housing.

Vermont's code is based on the International Energy Conservation Code, with specific provisions added as necessary. Like Minnesota, Vermont prohibits supply ventilation because of climate, but allows exhaust and balanced systems. Unlike Minnesota, it doesn't require ventilation to be continuous, but does require ventilation fans to be rated for (capable of) continuous operation.

Table 10. Prescriptive Requirements for Residential Ventilation Fan Capacity in Vermont
Sources: EDU 2000c, ICCI 2003

No. of bedrooms	Minimum Nominal Rated Capacity (cfm) of ventilation fans at 0.1" w.g.	Expected Actual Fan Capacity (cfm), assuming fans operate at 66% rated capacity
1	50	33
2	75	50
3	100	67
4	125	82
5	150	100
homes > 3,000 ft^2	5 cfm/100 ft^2	3.4 cfm/100 ft^2

Regarding airtightness, Vermont's code sets leakage or infiltration limits on a component basis (windows, exterior doors, recessed lighting fixtures, etc), not on a 'whole-house leakage' basis. It acknowledges the difference between rated and actual fan capacity (which is due to the difference between assumed (usually minimal) and actual system resistance, measured in inches water gauge) by assuming that ventilation fans will actually move only 66% of their rated capacity (VDPS 1998, Keefe & Cawley 1999, EDU 2000c, ICCI 2003). As shown in **Table 10** Vermont prescribes minimum ventilation rate based on number of bedrooms, and assuming actual flow is 66% of rated.

The preceding discussion of international, and state residential ventilation standards is intended to provide a basis for comparing and evaluating ASHRAE's new residential ventilation standard, whose recommendations are the focus of this thesis. However, following discussion of Vermont's standard, and before turning attention to Standard 62.2, this is a good time to reiterate that this thesis does not delve into the subject of fan physics, i.e., the impact of system resistance on actual fan flow. Rather, this thesis assumes that system designers take fan curves into account when selecting and installing ventilation fans, and that any discussion of mechanical ventilation rates refers to delivered (i.e., verified by measurement after installation), not nominal or rated flow.

6.8 ASHRAE Residential Ventilation Standard 62.2

ASHRAE decided in the late 1990s to create a separate but related standard for ventilation of residences, which is now known as Standard 62.2. The long and difficult process of developing ASHRAE *Standard 62.2–2003: Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings* has been chronicled elsewhere (Sherman 1999, EDU 1999b, EDU 2000a, EDU 2000b1, EDU 2001a, EDU 2001b, EDU 2001c, JLC 2001, EDU 2003). In short, over the course of five years (1999–2003) and four Public Review Drafts, which were furiously challenged by the natural-gas appliance and homebuilding industries, most of the original recommendations of building scientists on the 62.2 Project Committee were severely compromised or altogether eliminated. The following section summarizes the provisions of the resulting ASHRAE Standard 62.2–2003 that relate to the ability of mechanical ventilation systems sized according to the Standard to provide at least 0.35 AC/h in typical new U.S. houses.

6.8.1 Local Exhaust Ventilation Requirement

Section 5 of Standard 62.2 requires local exhaust fans in kitchens and bathrooms.[27] If intermittently operated by occupants, at least 100 cfm must be exhausted from kitchens and ≥ 50 cfm from baths (ASHRAE 2003). This requirement is consistent with Standard 62–2001 and most building codes, except they allow windows in lieu of exhaust fans in these rooms, while Standard 62.2 does not.

6.8.2 Whole-house Mechanical Ventilation System Requirement

With significant exceptions (described below), Standard 62.2 requires [28] that:

> "A mechanical exhaust system, supply system, or combination thereof shall be installed for each dwelling unit to provide whole-building ventilation with outdoor air each hour at no less than the rate specified in Table 4.1a and Table 4.1b or, equivalently, Equations 4.1a and 4.1b, based on the floor area of the conditioned space and number of bedrooms."

These tables and equations are reproduced in the next section. Exceptions to this requirement for mechanical ventilation are (1) homes in climates with less than 4500 °F-day (2500 °C-day) infiltration degree-days (IDDs), (2) homes in cooling climates (< 500 heating °F-day base 65 °F) without central air conditioning, or (3) vacation homes (those occupied less than 10% of each year), provided in all three cases that "the authority having jurisdiction determines that window operation is a locally permissible method of providing ventilation" (ASHRAE 2003).

The last two exceptions are reasonable, and it is unlikely that any authority would or could prohibit the use of windows for home ventilation. However, the first exception exempts homes in some very hot places, including Phoenix and Tucson Arizona, Las Vegas and Reno Nevada, Bakersfield and Fresno California, El Paso Texas, and large parts of Alabama, Florida, and

[27] Unless another method can provide the same exhaust rate, as certified by a licensed design professional.
[28] Unless an alternative (e.g., passive) ventilation system is approved by a "licensed design professional."

Georgia. In those areas, it is difficult to find homes being built *without* central air-conditioning, and even more difficult to imagine people having central air-conditioning in their homes and *not using it during the summer*, but opening their windows instead. One might reasonably conclude that this was a concession to the homebuilding industry, which is most prolific in the south and southwest. In any case, Standard 62.2 does not require homes in these areas to have a mechanical ventilation system.

6.8.3 Ventilation System Restrictions by Climate

Standard 62.2 "restricts" the use of exhaust ventilation systems in hot humid climates, and the use of supply ventilation systems in severely cold climates. Hot humid climates are defined as those

> "in which the wet-bulb temperature is 67 °F (19 °C) or higher for 3500 hours or more, or 73 °F (23 °C) or higher for 1750 hours or more, during the warmest six consecutive months of a year that is typical for that geographic area."

Hot humid climates include Hawaii and large portions of Alabama, Florida, Georgia, Louisiana, Mississippi, South Carolina, and Texas.

Standard 62.2 defines severely cold climates as having "more than 8000 annual heating degree-days base 65 °F-day (4400 annual heating degree-days base 18 °C-day)." These include Alaska and the northern parts of Maine, Michigan, Minnesota, Montana, North and South Dakota, Vermont, and Wisconsin.

However, these "restrictions" don't apply unless net exhaust fan flow in hot humid climates or net supply flow in severely cold climates exceeds 7.5 cfm per 100 ft^2 (5 L/s per 100 m^2). For example, we see from **Table 11** that the ventilation requirement for a 3000 ft^2 house is 45–105 cfm (depending on the number of bedrooms), while the climate restriction doesn't apply unless an unbalanced ventilation fan is at least (7.5 x 30 =) 225 cfm; i.e., the fan would have to be oversized (from the minimum) by 200–500% before its use was restricted by climate. Similarly, for a 1200 ft^2 house, the Standard limits unbalanced ventilation fans whose flow exceeds (7.5 x 12 =) 90 cfm; yet a 1200 ft^2 house would have to have *at least 8 bedrooms* before 90 cfm of ventilation is required. In other words, Standard 62.2's climate restriction on system type will likely never come into play.

6.8.4 Mechanical Ventilation Rate Requirements

In homes required to have a whole-house mechanical ventilation system, Section 4 of Standard 62.2 specifies minimum ventilation (outdoor air supply) rates according to conditioned floor area and number of bedrooms.[29] Specifically, it requires mechanical ventilation of at least 1 cfm per 100 ft^2 (0.5 L/s per m^2) of floor area *plus* 7.5 cfm (3.5 L/s) per occupant. **Table 11 and Equation 9** correspond to Tables and Equations 4.1a (IP units) and 4.1b (SI units) of the Standard.

The first Public Review Draft of Standard 62.2P (proposed), August 2000, specified *twice* as much outdoor air per occupant as did the final Standard: 15 vs 7.5 cfm/person, respectively.

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[29] Like Standard 62, Standard 62.2 assumes the occupancy of a home is one person per bedroom plus one additional person in the master bedroom. Of course, actual occupancy should be used if it is known to be higher, but that is seldom the case when designing ventilation systems for new homes.

Table 11. Ventilation Air Requirements, from ASHRAE Standard 62.2–2003

a. (IP) Outdoor Air Required, cfm						b. (SI) Outdoor Air Required, L/s					
Floor Area	**No. of Bedrooms**					**Floor**	**No. of Bedrooms**				
(ft^2)	**0-1**	**2–3**	**4–5**	**6–7**	**>7**	**Area (m^2)**	**0–1**	**2–3**	**4–5**	**6–7**	**>7**
< 1500	30	45	60	75	90	< 139	14	21	28	35	42
1502–3000	45	60	75	90	105	139.1–279	21	28	35	42	50
3001–4500	60	75	90	105	120	279.1–418	28	35	42	50	57
4501–6000	75	90	105	120	135	418.1–557	35	42	50	57	64
6001–7500	90	105	120	135	150	557.1–697	42	50	57	64	71
> 7500	105	120	135	150	165	> 697	50	57	64	71	78

a) $Q_{fan} = 0.01 A_{floor} + 7.5(N_{br} + 1)$ b) $Q_{fan} = 0.05 A_{floor} + 3.5(N_{br} + 1)$ (9)

where Q_{fan} = fan flow rate in cfm Q_{fan} = fan flow rate in L/s
A_{floor} = floor area in ft^2 A_{floor} = floor area in m^2
N_{br} = no. of bedrooms (≥1) N_{br} = no. of bedrooms (≥1)

6.8.5 Infiltration Credit

Table 11's mechanical ventilation requirements assume "a default credit for ventilation provided by infiltration of 2 cfm/100 ft^2 (10 L/s per 100 m^2) of occupiable floor space." In contrast, the first Public Review Draft specified *half* as much credit for infiltration as did the final Standard: 1 cfm/100 ft^2 vs 2 cfm/100 ft^2 floor area, respectively (ASHRAE 2000, ASHRAE 2003).

Apparently, doubling of uncontrolled 'ventilation by building leakage' (from 1 to 2 cfm/100 ft^2) offsets the halving of controlled mechanical ventilation per occupant (from 15 to 7.5 cfm/person). One might conclude this was another concession to the homebuilding industry, given this explanation by Max Sherman, chairman of Standard 62.2P's Project Committee (EDU 2001a):

> "Our thinking about the minimum ventilation requirements for people has not really changed… But in response to the comments we received, the committee was persuaded that it's appropriate to raise the infiltration credit to 2 cfm per 100 ft^2 — reflecting typical house leakage — and to lower the fan requirement to 7.5 cfm per person."

Wray et al (2000) explains the rationale for the original 1 cfm/100 ft^2 infiltration credit:

> "This infiltration credit is based on weather for a presumed critical week and on a very airtight building envelope (normalized leakage of 0.125 (dimensionless), normalized (by) floor area and building height). The critical week occurs when the weather is extreme enough that occupants no longer open their windows for the remainder of the season, which may vary (between climates). Although actual infiltration is dependent on climate and normalized leakage, the magnitude of the credit remains independent of these parameters.
>
> "In fact, infiltration may be quite different from this assumption, especially for the housing stock as a whole. The Standard takes the conservative position that only a small, fixed infiltration credit is appropriate to avoid 'gaming' or providing the counter-productive incentive to poke holes in a tight building envelope…"

Wray et al (2000) and a related paper (Sherman 1999) also explain that, to avoid having to install mechanical ventilation systems in houses that are much leakier than the Standard assumes (and therefore have adequate natural, if uncontrolled, ventilation), 62.2P allows credit to be taken for *actual* infiltration, if leakage is measured with a blower door per ASHRAE Standard 119.

By corollary, a doubling of the infiltration credit originally assumed by Standard 62.2 effectively:

- assumes an infiltration credit that is more typical of new home construction,
- provides a counter-productive incentive to 'poke holes' or make the building less tight,
- removes the incentive to measure and account for actual building leakage when designing the mechanical ventilation system, and
- increases the likelihood that new homes built *tighter* than the infiltration credit assumes — i.e., those most in need of mechanical ventilation—will not receive adequate ventilation.

6.8.6 Comparing Ventilation Rates between ASHRAE Standard 62 and Standard 62.2

Standards 62 and 62.2 specify minimum ventilation rates differently; Standard 62 requires 0.35 AC/h or 15 cfm/person, whichever is greater, while Standard 62.2 requires 7.5 cfm/person *plus* a rate based on house floor area (which is obtained either from a table or an equation). In order to compare the ventilation rates required by the two standards, it is first necessary to calculate the ventilation rate required by Standard 62. For example, in a 2000 ft^2 3-bedroom home with 8' ceilings, the building volume (one air change) is 16,000 ft^3, so 0.35 air-changes/hour would require a (0.35 AC/h x 16,000 ft^3/AC ÷ 60 min/hr =) 93 cfm fan according to Standard 62, compared to a 60 cfm fan required by Standard 62.2 (**Table 11**). That is a big difference in ventilation fan size— big enough that designers might be expected to question and try to account for such a discrepancy.

Table 12 compares ventilation rates of the two standards across a range of typical house sizes. The discrepancy between the Standards is attributable to Standard 62.2's implicit assumption that infiltration contributes a significant portion (~43%) of the minimum ventilation rate, regardless of house size, and apparently also regardless of weather conditions and house tightness.

Table 12. Comparison of Standard 62 and Standard 62.2 Ventilation Rates

House size		Standard 62	Standard 62.2 ventilation rate			Standard 62.2 as % of Standard 62		
floor area ft^2	bed-rooms no.	recommended minimum ventilation rate cfm	fan size: mechanical ventilation cfm	infiltration: uncontrolled, assumed cfm	combined, IF fan flow is additive to infiltration cfm	mechanical component, controlled	infiltration component, assumed	combined, IF fan flow is additive to infiltration
1200	1	56	27	24	51	48%	43%	91%
1200	2	56	35	24	59	62%	43%	104%
1200	3	60	42	24	66	70%	40%	110%
1800	2	84	41	36	77	48%	43%	91%
1800	3	84	48	36	84	57%	43%	100%
1800	4	84	56	36	92	66%	43%	109%
2400	3	112	54	48	102	48%	43%	91%
2400	4	112	62	48	110	55%	43%	98%
2400	5	112	69	48	117	62%	43%	104%
3000	4	140	68	60	128	48%	43%	91%
3000	5	140	75	60	135	54%	43%	96%
3000	6	140	83	60	143	59%	43%	102%
3600	5	168	81	72	153	48%	43%	91%
3600	6	168	89	72	161	53%	43%	96%
3600	7	168	96	72	168	57%	43%	100%
					min	48%	40%	91%
					average	**56%**	**43%**	**98%**
					max	70%	43%	110%

Apparently, Standard 62.2 also assumes that ventilation fan flow and (assumed) infiltration rate are additive, because when these values are added together, their sum approximates (within 10%) the minimum ventilation rate recommended by Standard 62. This assumption was confirmed to me by Sherman (2003), chairman of the Standard 62.2 Committee, To most people, this might appear to resolve the discrepancy between the rates recommended by Standards 62 and 62.2.

However, residential building scientists should recognize at least two problems here. The first and most obvious problem is that actual infiltration is not nearly so stable or reliable as 62.2 assumes, but varies enormously (a) between houses according to their tightness, height, leakage distribution, and exposure, and (b) over time in the same house depending on the changing forces of stack effect, wind, and interior fans and doors. The second, less obvious problem is that the flow of unbalanced fans *is not additive* to infiltration.

6.9 Superposition: Combining Infiltration and Mechanical Ventilation

Some residential building scientists spent the early 1980s working to understand and predict the interaction of wind and stack effect; many of the same scientists spent the early 1990s trying to understand and predict the interaction of natural infiltration and mechanical ventilation. In the 1980s blower doors were used mainly to characterize and 'optimize' building leakage areas, as exemplified by home weatherization efforts. Over time, residential building scientists began to appreciate the benefits of making (at least new) houses as tight as possible and ventilating them mechanically. About 1990, their focus began to shift toward studying the interaction of mechanical ventilation fans and natural infiltration, in order to properly design mechanical ventilation systems. Just as comparisons of tracer gas and blower-door measurements were used to *develop* the LBL model in 1980, tracer gas measurements were used to *improve* the LBL model in the early 1990s, in particular the methods of 'superposing' natural and mechanical driving forces (Kesselring 1991).

Envelope leaks and infiltration are highly variable but always present to some degree in houses. Fan-driven airflow supplements but is not necessarily additional to infiltration because the two interact in complex ways. Since 1991, building scientists have realized that unless the flow through an unbalanced fan is much greater than infiltration, the *ventilation added by the fan* will be only half its actual flow. For example, a house with 60 cfm of infiltration and a fan exhausting 80 cfm of air will have a ventilation rate of 100 (not 140) cfm.[30] This principle is called the "0.5 rule" (Palmiter & Bond 1991) or "50% rule" (Sherman 1992) and has been incorporated into ASHRAE Fundamentals since 1993. This thesis calls it the "Half-Fan Rule" and examines its impact on ventilation rates in new houses that have exhaust ventilation fans sized according to Standard 62.2.

6.9.1 Palmiter's Half-Fan Rule

From 1988–1990, the Washington State Energy Office (WSEO) commissioned a series of studies by ECOTOPE, a building science research and consulting firm in Seattle, to evaluate infiltration and ventilation rates in new electrically-heated homes in the Pacific Northwest. ECOTOPE compared infiltration rates predicted by the LBL model (based on blower-door measurements of leakage area) to those measured with tracer gas in a total of 472 new homes (312 site-built and 160 manufactured homes). Of the 312 site-built homes, 129 had some kind of mechanical ventilation system. and 131 of the 160 manufactured homes had an exhaust ventilation system.

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[30] Given building volume, cfm is easily converted to AC/h. Building volume is one air change: ft3/minute x AC/ft3 x 60 minutes/hour = AC/hour.

Among many other findings, researchers from both ECOTOPE (Palmiter) and LBL (Sherman) found that "(e)ven in the fairly tight test homes, (unbalanced) fans typically delivered only half their rated capacity" (Kesselring 1991). From Palmiter (1990):

> "Generally, the amount of air flow added by the ventilation system is considerably smaller than the amount of air flow through the ventilation system. This is particularly true of exhaust-only systems. When the exhaust fan is turned on, pressures across the envelope become more negative.
>
> "…Only when there are no pressures due to wind and stack effect will a 100 cfm (exhaust) fan.. induce additional infiltration equal to the full capacity of the fan. Up to the point where all natural outward flows are reversed, the fan will induce additional ventilation of exactly half its capacity…
>
> "Of course, the total infiltration with the fan operating will never be less than the flow through the fan, nor will it be less than the natural infiltration."

Measured data were so consistent that the researchers developed a simple model for predicting both additional infiltration induced by unbalanced fans and the total ventilation rate. From EPRI (1991):

> "The basic idea of the model is very simple. For any given moment in time, it is assumed that the total infiltration is the net fan flow when the…net flow…due to all fans in operation is greater than twice the predicted natural infiltration rate. The added infiltration is then the net fan flow minus the predicted natural infiltration.
>
> "When the net fan flow at some moment is less than twice the predicted natural infiltration rate, the added infiltration is one-half the net fan flow and the total infiltration is the sum of the natural and one-half the (unbalanced) fan flow.

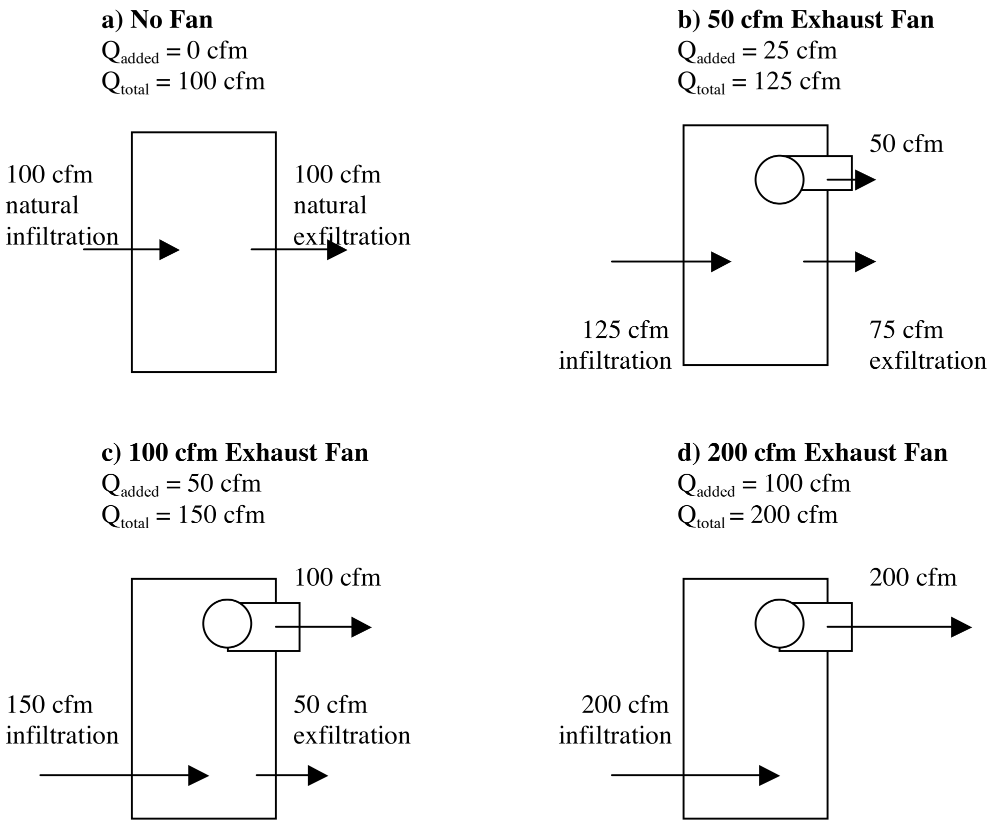
The term "net fan flow" allows for a 'balanced' system (with both exhaust and supply fans) that are not, in fact, balanced; in such a case "net fan flow" is the unbalanced portion of their flow. For an exhaust-only ventilation system, "net fan flow" simply equals the exhaust fan flow.

Figure 3 and **Table 13** are derived from Figure and Table 5.1, respectively, of that report. In **Figures 3b** and **3c** the total ventilation rate is considerably higher than fan flow rate, but the fan actually contributes only half its flow as additional ventilation (above the natural infiltration rate); the majority of ventilation is from natural infiltration. Notice that total ventilation does not equal exhaust fan flow until exhaust fan flow is twice the natural infiltration rate. Notice also that when fan flow *is* twice natural infiltration (**3d)**, the fan still contributes only half its flow (100 cfm) as additional ventilation; the rest would occur naturally as infiltration. And in no case with an exhaust fan does the total ventilation equal natural infiltration plus fan flow.

Table 13. Empirical Testing of Half Fan Rule
(source: EPRI 1991, page 5-3)

Site	Fan Description	Measured Fan Flow (cfm)	Change in Infiltration (cfm) Measured	Change in Infiltration (cfm) Predicted	Ratio
1	multiport exhaust	75	37.0	37.5	0.987
2	1st floor bathroom exhaust	27	13.5	13.5	1.000
3	central singleport exhaust	50	25.8	25.0	1.032
4	kitchen range exhaust	67	30.7	33.5	0.916

Figure 3. Illustration of the Half Fan Rule
(derived from: EPRI 1991, page 5-2)
Q_{added} is the amount of ventilation added by the exhaust fan.



Again, the Half Fan Rule is a model derived from and verified by empirical testing. **Table 13** shows results of an experiment designed to test the model by comparing it to measured values.

Concluding discussion of their "fan infiltration model," ECOTOPE and LBL researchers state:

> "This has important implications for sizing exhaust or supply ventilation systems…It requires an extremely tight home or a large fan (or several operating at once) to reach the point where the fan flow exceeds twice the natural infiltration rate."

In a subsequent report, Palmiter & Bond (1991) go on to define "fan efficiency" E, as the ratio of the added flow induced by the fan to the fan flow:

$$\mathrm{E} = \frac{Q_{\inf} - Q_{nat}}{Q_{fan}} \tag{10}$$

where Q_{inf} = total infiltration, both naturally and mechanically induced,
Q_{nat} = naturally induced infiltration,
Q_{fan} = flow through the fan

6.9.2 Sherman's 50% Rule

Subsequent to the 1991 EPRI report, Sherman (1992) also introduced the concept of "fan addition efficiency":

> "(I)n general (small, unbalanced) fans contribute approximately 50% of their actual flow rate towards increasing the total ventilation. Such efficiencies must be considered when making either energy or indoor air quality calculations…
>
> "The fan addition efficiency, E_F, indicates the contribution an unbalanced mechanical ventilation system has on the total ventilation: $0 < E_F \leq 1$ When little is known about the details of the system, the 50% rule…can be used as default."

Prior to development of the Half Fan Rule, the 1989 edition of ASHRAE Fundamentals combined natural and mechanical driving forces much as it combined wind and stack forces — quadratically—except for balanced mechanical flows, which were additive. The equation for superposition of natural and mechanical flows was:

$$Q = Q_{bal} + \sqrt{Q_{unbal}^2 + Q_{ws}^2} \tag{11}$$

where Q = total ventilation rate,
Q_{bal} = balanced fan flow rate,
Q_{unbal} = unbalanced fan flow rate, and
Q_{ws} = naturally induced infiltration rate (due to wind and stack)

Following Palmiter and Sherman's revelations about the ~50% efficiency of unbalanced fans, the 1993 edition of ASHRAE Fundamentals provided the following method for superposition of fans:

$$Q = Q_{bal} + Max(Q_{unbal}, Q_{ws} + 0.5Q_{unbal}) \tag{12}$$

ASHRAE Standard 136–1993: *A Method of Determining Air Change Rates in Detached Dwellings* also incorporated the Half Fan Rule, and the same superposition equation was repeated in Fundamentals 1997, but with the following elaboration for residential buildings:

> "The following method is used in ASHRAE Standard 136.
>
> 1. If the ventilation supply and exhaust flow rates are balanced, then they are simply added to the infiltration flow rate.
> 2. If the ventilation supply and exhaust flow rates are unbalanced and much larger than the infiltration rate, then infiltration may be ignored.
> 3. If the unbalanced flow rate is much smaller than the infiltration flow rate, only half is counted: $Q_{comb} = Q_{bal} + \frac{Q_{unbal}}{2} + Q_{\inf}$
> 4. If the unbalanced flow rate is not much larger or much smaller than the infiltration flow rate, then the combined flow rate is: $Q_{comb} = Q_{bal} + \sqrt{Q_{unbal}^2 + Q_{\inf iltration}^2}$

However it may be called, the 'Half Fan Rule' is an established principle of building air flow.

6.10 Evaluation of Ventilation System Performance

The title of this report indicates that it evaluates the performance of residential ventilation systems. There are in fact many methods for assessing ventilation system performance; technical literature on the subject is extensive. Because the parameters and their definitions vary so widely, it is essential to clarify rather than assume their meaning, at least within a given report. Full review of this subject is beyond the scope of this paper,[31] but I will summarize as necessary to describe and justify the parameters I use to evaluate mechanical ventilation system performance in new houses.

It is helpful to think about residential mechanical ventilation as two separate but related processes, (1) the flow of air between indoors and out, or airflow through the envelope, and (2) the flow of air within a house, i.e., how well incoming air mixes with indoor air as air moves through the house. In their 1996 book *Building Ventilation: Theory and Measurement* Etheridge and Sandberg wrote:

> "The ventilation of a space can be considered as two distinct simultaneous processes. The first is the flow of air though openings in the external envelope… The second is the motion of air inside the space. This division is more than just a descriptive convenience. Its is fundamental to the investigation of ventilation, whether by theoretical or experimental means. The first process is… virtually independent of the second… The second process is much more dependent on the first…"

Ventilation standards usually address only the first process, by specifying a minimum 'air change' or 'outdoor air supply' rate (e.g., "≥ 0.35 AC/h"). It is relatively easy to estimate air exchange rates by using a simplified mathematical model (e.g., the LBL infiltration model) to account for the interaction of climate, building leakage area (blower-door measurements), and any ventilation fans. It is much more difficult, however, to evaluate the second process—air distribution within homes.

In *A Guide to Energy Efficient Ventilation,* Liddament (1996) presents an international consensus[32] regarding the performance parameters of "air change efficiency" and "contaminant (or pollutant) removal effectiveness." Both depend on indoor air distribution, but 'effectiveness' also depends on the characteristics of indoor pollutants, particularly their source strengths and spatial distribution. 'Air change efficiency' is a function of how well incoming air mixes with air already present in the space. Pure piston (i.e., plug) flow is 100% efficient, while thorough mixing of indoor air—which is the goal of forced-air conditioning systems—yields an air change efficiency of 50% at best. However, ventilation rates can vary considerably from room to room, depending on how air flows through the house. 'Pollutant removal effectiveness' measures the impact of this efficiency on pollutant concentrations. However, no correlation has been found between air change efficiency and pollutant removal effectiveness (Seppanen 1986, Helenius et al 1987).

Air-change efficiency and pollutant removal effectiveness are important to system performance, but their evaluation is beyond the scope of those designing residential ventilation systems—and beyond the scope of this thesis—because of two profound limitations (Liddament 1993):

1) they can only be evaluated by physical measurement with tracer gases or with computers modeling computational fluid dynamics (CFD), both of which are so complex, costly, and time-consuming as to be limited to the realm of well-funded academic research, and

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31 More complete reviews of these concepts are given by Seppanen (1986), Etheridge & Sandberg (1996), and Liddament (1996).

32 At least among members of the Air Infiltration and Ventilation Centre (AIVC), based in Great Britain and whose members include Belgium, Canada, Denmark, France, Norway, Sweden, Switzerland, and the USA.

2) tracer gas measurements can only be made in existing buildings, and it can be difficult to extrapolate the results beyond the specific outdoor and indoor conditions (temperature, door position, etc) prevalent during measurement.

Designers of residential ventilation systems can't be expected to perform tracer gas measurements or CFD simulations, but they can and should learn from and incorporate the lessons offered by those who do. Two of the most relevant research findings are summarized here.

- Closed interior doors reduce the performance of singleport exhaust ventilation systems much more than that of balanced, supply, or multiport exhaust systems (Haghighat et al 1990, Kesselring 1991). Thus, singleport exhaust ventilation is most appropriate for homes with little or no resistance to airflow, e.g., those with open floor plans and few interior doors.
- Balanced ventilation systems add the full flow of one fan (not both) to the ventilation rate, so they are much more likely (than unbalanced fans) to meet the minimum ventilation rate. However, infiltration impacts the efficiency of balanced systems even more than that of unbalanced systems. Any reduction in efficiency is especially important for balanced systems that include heat recovery because the more uncontrolled infiltration there is, the less ventilation air actually passes through the fans, and thus any heat exchanger (Feustel et al 1986, Harrje & Gadsby 1986, Binamu & Lindberg 2000, ASHRAE 2001). In other words, while building airtightness is very important to the performance of unbalanced ventilation systems, it is even more critical to the performance of balanced heat-recovery ventilation systems. (This fact should also be evident from the preceding discussion of international ventilation and tightness standards.)

This analysis will focus on whole building air-change rates because we recognize that in order for ventilation air to reach occupants and dilute indoor pollutants, it must first *enter the building*.

This thesis evaluates exhaust ventilation system performance on the basis of three parameters—in relative order of importance—which are listed here and described further under **Methods** :

1) Whole-house ventilation rates, in AC/h (averaged over each day, week, and month),
2) Exhaust ventilation efficiency, as a proxy for the efficacy of the ventilation fan, and
3) The stability or consistency of ventilation rates, as measured by their standard deviation.

The minimum residential air-change rate established by Standard 62 is 0.35 AC/h, which begs the question: "Should air-changes per hour be averaged over each day, week, or month?" If averaged over an entire year, a rate of 0.35 AC/h is likely to mask significant periods of lower ventilation (e.g., in spring and fall), which are offset by periods of higher ventilation (e.g., during winter). One major limitation of both Standard 62 and 62.2 is that neither indicates or discusses the appropriate interval(s) for averaging air changes per hour. This thesis will average and compare AC/h values over each hour, day, week, and month so readers can make their own comparisons.

ASHRAE's minimum ventilation rate of 0.35 AC/h, which has prevailed in the U.S. since 1989, is somewhat arbitrary, unavoidably controversial, and subject to change. However, this thesis does not argue with that rate, and until it changes we will use it as a benchmark to determine adequate ventilation. There is no corresponding upper limit for home ventilation, but in the interest of minimizing operating costs, including those associated with conditioning ventilation air, the rate of 0.70 AC/h is often used (Persily 1998). We categorize ventilation rates as follows:

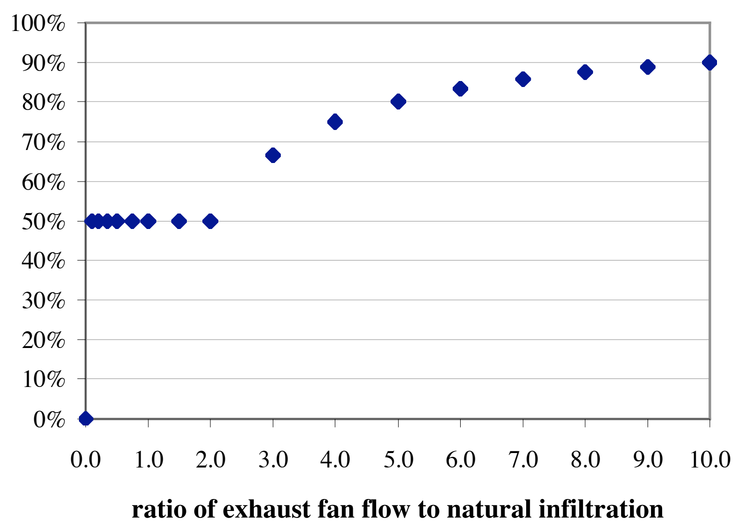
- Under-ventilation, < 0.35 AC/h
- Adequate ventilation 0.35–0.70 AC/h, and
- Over-ventilation > 0.70 AC/h.

Of course, the distinct demarcation implied by these categories does not occur in reality, and there is no guarantee that 'adequate ventilation' by any definition results in acceptable indoor air quality. Rather, this is a reasonable simplification that we make for purposes of this analysis.

The primary objective of residential ventilation standards (and this thesis) is to ensure adequate air exchange rates in homes, because (except for source control of indoor pollutants) that is the first step toward minimizing occupants' exposure to indoor pollutants that might impact their health. A secondary goal of mechanical ventilation system design should be to optimize the percent of total ventilation that passes through the ventilation fan, because the ultimate goal is for the ventilation fan to control or regulate the indoor-outdoor air exchange rate.

Palmiter defines "exhaust fan efficiency," E, as the added ventilation induced by the fan divided by the *exhaust fan flow* (**Equation 10**)*;* Sherman calls this same value "fan addition efficiency." According to that definition, the exhaust fan always contributes at least half its flow as additional ventilation, so the fan efficiency is never lower than 50%, as seen in **Figure 4a.**

Figure 4a. Palmiter & Sherman's "Fan Addition Efficiency"
(= flow added by the exhaust ventilation fan ÷ exhaust fan flow)

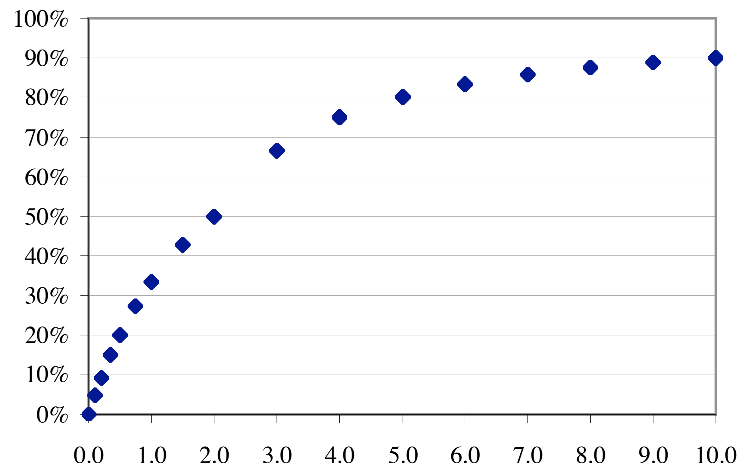


This thesis adapts Palmiter & Sherman's concept of fan addition efficiency for use as a proxy for the relative cost-effectiveness of exhaust ventilation. We're interested in what portion of the total ventilation rate is attributable to the ventilation fan, so we define "exhaust ventilation efficiency" as the added ventilation induced by the exhaust fan divided by the *total ventilation rate*, as shown in **Equation 13** and **Figure 4b**. By this definition, exhaust ventilation efficiency is less than 50% if the ratio of fan flow to natural infiltration is < 2.

$$\mathrm{E} = \frac{Q_{total} - Q_{nat}}{Q_{total}} \quad (13)$$

where Q_{total} = total infiltration, both naturally and mechanically induced,
Q_{nat} = naturally induced infiltration, and
$Q_{total}–Q_{nat}$ = infiltration induced (i.e., ventilation added) by the exhaust fan

Figure 4b. Proposed "Exhaust Ventilation Efficiency"
(= flow added by the exhaust ventilation fan ÷ total ventilation)



Figures 4a and **4b** are based on calculations using Palmiter's Half-Fan (or Sherman's 50%) Rule. **Appendix B** is a table of the Half Fan Rule calculations on which **Figures 4a** and **4b** are based. Again, the curves are the same except **Figure 4a** divides the ventilation contribution of the exhaust fan by the exhaust fan flow, while **Figure 4b** divides the ventilation contribution of the exhaust fan by the total ventilation rate; according to the former definition, efficiency is never less than 50%. The greatest increase in efficiency appears to occur when the exhaust fan flow is between 2 and 3 times larger than natural infiltration (resulting in efficiencies of 50% to almost 70%, respectively).

Based on the calculations in **Appendix B**, efficiency (defined either way) can theoretically reach 100%, but not until exhaust ventilation fan flow is 200 times larger than infiltration. That would require either an extremely small tight house and/or an excessively large exhaust fan; obviously, there is a trade-off or balance point between the size of the exhaust fan and the efficiency of the system, with diminishing returns (in terms of added ventilation) from increasing exhaust fan size. This thesis will calculate the 'exhaust ventilation efficiency' for scenarios with an exhaust fan.

Finally, we will evaluate the impact of tightness and fan size on the consistency or stability of each scenario by calculating and comparing the relative standard deviation of air-change rates because (all else being equal) the more consistent the ventilation rate, the lower the quantity of outdoor air that needs to be conditioned.

7 Statement of Problem, Objectives

Building codes and standards exist primarily to ensure minimum levels of safety and health, and secondarily to promote effectiveness (functionality) and encourage energy- or resource-efficiency. The primary function of residential mechanical ventilation, therefore, is to protect occupants from unsafe and unhealthy levels of indoor air pollutants and secondarily, to do so as efficiently and effectively as possible. Besides source control, the best way to ensure acceptable air quality in new homes whenever windows are closed is to provide a continuous minimum rate of ventilation, or air exchange; since 1989, ASHRAE has recommended ≥ 0.35 AC/h.

This thesis challenges the ability of exhaust fans sized according to the new ASHRAE residential ventilation Standard 62.2 to ensure ≥ 0.35 AC/h in new homes. Standard 62.2 sizes whole-house ventilation fans well below the minimum 0.35 AC/h recommended by ASHRAE, assuming that infiltration contributes the remainder of this minimum ventilation rate. Yet, according to ASHRAE Fundamentals, unless the flow through an unbalanced (exhaust or supply) ventilation fan is at least twice the natural infiltration rate, the fan contributes only half its flow as additional ventilation. In most new homes, when windows are closed, infiltration is often low enough to need mechanical supplement, but not low enough to be dominated by an exhaust fan sized according to the Standard. In those conditions—according to ASHRAE Fundamentals—the house ventilation rate is *not* the infiltration rate plus the ventilation fan flow rate, it is the infiltration rate plus *half* the fan flow rate.

This thesis identifies and addresses two problems with the way Standard 62.2 is currently written. First, the Standard assumes all new homes have the same, constant infiltration rate, and second, it assumes infiltration and ventilation fan flow are additive, and combine to provide ≥ 0.35 AC/h. Because of these incorrect assumptions, many new homes could be significantly under-ventilated.

At best, when infiltration is the same or higher than assumed, exhaust ventilation is less efficient in terms of its contribution to air exchange, and its costs become more questionable, less justifiable; the house is more likely to be adequately ventilated, but there is no guarantee against under- or over-ventilation. At worst, infiltration is much lower than assumed, in which case the ventilation rate equals the exhaust fan flow, but the house remains under-ventilated because the exhaust fan is under-sized. In between are situations in which infiltration is lower than assumed, but not low enough to be dominated by an exhaust fan; the fan then contributes half its flow, which, combined with infiltration, leaves the house under-ventilated. In fact, the tighter the house—i.e., the more its occupants *need* mechanical ventilation—the less likely they are to receive adequate ventilation.

Considering the lack of pollutant source control in most new houses, it is difficult to understand why ASHRAE would undermine its own prescribed minimum residential ventilation rate, which is already the lowest in the world. Those most at risk from this situation are conscientious builders who build tighter houses, then rely on Standard 62.2 to size exhaust ventilation fans. Their reward for setting a good example is increased exposure to liability for under-ventilation, and their clients' increased risk of poor home indoor air quality and any detrimental effect on their family's health.

The primary objective of this thesis is to demonstrate that exhaust ventilation fans sized according to Standard 62.2 as currently written will not ensure at least 0.35 AC/h in new homes. The second objective is to recommend a method of sizing exhaust ventilation fans to ensure that—regardless of their tightness—new homes are assured of the recommended minimum ventilation rate. A third objective is to demonstrate that—once the priority of ensuring minimum ventilation rates has been achieved—mechanical ventilation performance can be improved by building tighter houses.

8 Methods

To demonstrate ventilation rates likely to occur in homes, this thesis employs the multi-zone model CONTAM, which incorporates ASHRAE-accepted principles of airflow through buildings. This model allows us to conduct a parametric analysis of the interaction between building tightness and exhaust fan size on air-change rates in a typical new house over a typical meteorological year.

From the foregoing **Background** section it should be apparent that actual home ventilation rates are influenced by many variables, including house size and configuration, local weather conditions, building airtightness, and ventilation fan size. It is not possible for this (or any other) study to characterize ventilation rates for all combinations of these variables that occur throughout the U.S. It is therefore necessary to selectively limit the variables to those most relevant to the task at hand. Because our focus is on the impacts of building tightness and exhaust fan size on ventilation rates, we simplify our analysis by simulating a single (typical new) house in a single moderate climate.[33] Our variables are building airtightness and ventilation fan size; we will model three values of each.

First we design a virtual house that is, to the extent possible, typical of new homes built in the U.S.; then we 'construct' it within the CONTAM model. Next we select the combinations of variables (house airtightness and exhaust ventilation fan size) to be tested and create a CONTAM project file for each scenario. This study includes nine scenarios, the product of three tightness levels and three exhaust ventilation fan sizes, which are listed in **Table 14**. The 'no fan' case is necessary for establishing a baseline of air exchange in the absence of an exhaust ventilation fan, to be subtracted from the air exchange with an exhaust ventilation fan in order to calculate 'exhaust fan efficiency.'

Table 14a. Variables Modeled in CONTAM

Source of house airtightness levels: Sherman 2002 (see Table 6)

variable	name	code	description	value
exhaust ventilation fan size	no fan	**V0**	no exhaust ventilation fan	0 cfm
	per 62.2	**V75**	exhaust fan sized per Standard 62.2, Table	75 cfm
	0.35 AC/h	**V126**	exhaust fan sized to deliver 0.35 AC/h	126 cfm
house airtightness level	AKWarm	**NL23**	average of tightest new houses in Alaska	NL 0.23
	Efficient	**NL31**	average of new energy-efficient houses	NL 0.31
	Typical	**NL55**	average of typical new U.S. construction	NL 0.55

Table 14b. Scenarios Modeled in CONTAM

code	V0	V75	V126
NL23	NL23_V0	NL23_V75	NL23_V126
NL31	NL31_V0	NL31_V75	NL31_V126
NL55	NL55_V0	NL55_V75	NL55_V126

In summary, one tightness scenario (NL55) represents the average tightness of typical new houses; another (NL31) represents an average of houses built in energy-efficient construction programs (in the lower 48 states), which usually emphasize air-tightness; and the third scenario (NL23) is an average of the tightest levels achieved in new U.S. houses, all of which are built in Alaska. Notice that the 'loosest' house modeled in this study is also the *average* of typical new construction, so many new U.S. houses are actually looser than any modeled in this study.

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[33] Results will vary for different climates. In general, the colder the climate, the stronger the forces that drive infiltration and the more important building tightness becomes to heating, cooling and ventilating efficiency. We chose a moderate climate because the majority of new U.S. houses are built in the sunbelt.

Next we select a single location—with moderate weather—in which to test our scenarios. While there is no such thing as 'average weather,' we select a location that is as moderate in all respects (described below) as any in the U.S. We then use the CONTAM model and TMY2 (typical meteorological year) weather data to simulate AC/h for every hour of the year, for nine scenarios. Air change rates from each scenario are averaged over each day, week, and month for comparison with the minimum 0.35 AC/h. 'Exhaust ventilation efficiency' is calculated as the ratio of added ventilation to total ventilation. Each of these steps is described in more detail below.

8.1 Define a Typical New U.S. House

We use information provided in **New Home Construction in the U.S.** to select parameters most characteristic of new detached single-family homes. Based on that information, we assume that our virtual house is built by a production building company and has the following characteristics:

- located in the South or West
- slab-on-grade foundation
- 2400 ft^2 (223 m^2) floor area
- 2 storeys
- 4 bedrooms (5 occupants), 2.5 baths
- central forced-air conditioning
- attached 2-car garage
- average 9 ft (2.7 m) ceiling height

We're using exhaust ventilation in a home with an attached garage after recommending against it because attached garages are almost as common in new homes as central AC, and while not part of this thesis, we hope to eventually calculate the percent of ventilation air coming from the garage.

In our virtual new home, 14% of total leakage area is in the forced-air ducts. Actual percentage of leakage attributable to the duct system varies widely, e.g., from 5–30% (Cummings 1989, Yuill & Musser1997). Thirty percent is often considered typical of existing homes, so in essence, we are assuming new homes have about half as much forced-air duct leakage as existing homes.

Our CONTAM model also incorporates the following assumptions about our typical new house:

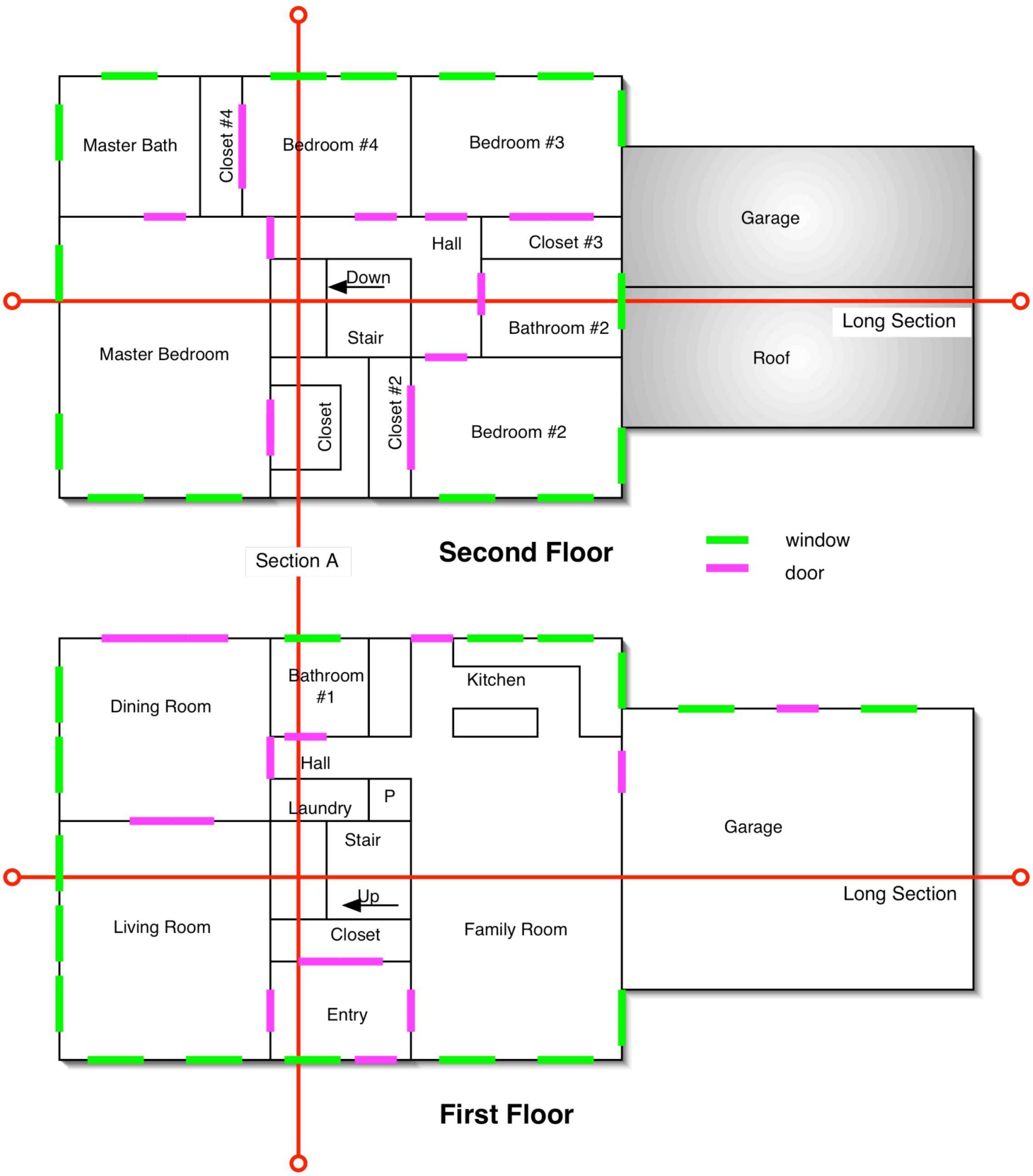
1) it has a rectangular footprint of 30' x 40' (1200 ft^2 x 2 storeys = 2400 ft^2),
2) it is located in suburban terrain, with a corresponding wind shielding class,
3) window area is 18% of floor area, and all windows are 4'x 3' horizontal sliders,
4) all exterior doors are 3' x 6.7' (20 ft^2) each, except one 10' x 7' sliding glass door,
5) if there is a fireplace or gas appliance, its zone is completely sealed from the living space,
6) if there is any ground-source radon, it is removed by its own sub-slab ventilation system,
7) each bathroom has a 50 cfm spot exhaust fan; the kitchen has a 100 cfm range exhaust,
8) the heater and AC are in the attic, which is unconditioned and vented per code,[34]
9) indoor set-point temperature is 70°F in winter (November–March), and 75°F in summer,
10) there is one forced-air return grille per storey, and at least one supply grille in each room,
11) forced-air ducts are located in the walls and ceilings; air is supplied at the ceiling,
12) interior doors remain open, except bedroom doors are closed 8 hours each night, and
13) exterior doors remain closed (i.e., the time they spend open is insignificant).

The reason for 'closing' bedroom doors at night is to capture the impact of closed interior doors on house air change rates, as well as to be able to eventually calculate air exchange rates in bedrooms.

[34] 1 m^2 free vent area per 300 m^2 attic 'floor area'

Figures 5-7 illustrate the design, layout, and configuration of our virtual new house.[35] In terms of elevation, the first floor (slab) is one foot above grade, the second floor is 10 feet higher (9' ceiling height + 1' floor construction), and the attic floor is another 10'—or 21' above grade. The roof peak is 8' above the attic floor—29' above grade. The stair is open and centrally located.

Figure 5. Typical New House: Plan
(no scale)



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[35] These drawing were generated using OmniGraffle 2.2 software, available from the Omni Group.

Figure 6. Typical New House: Section A
(no scale)

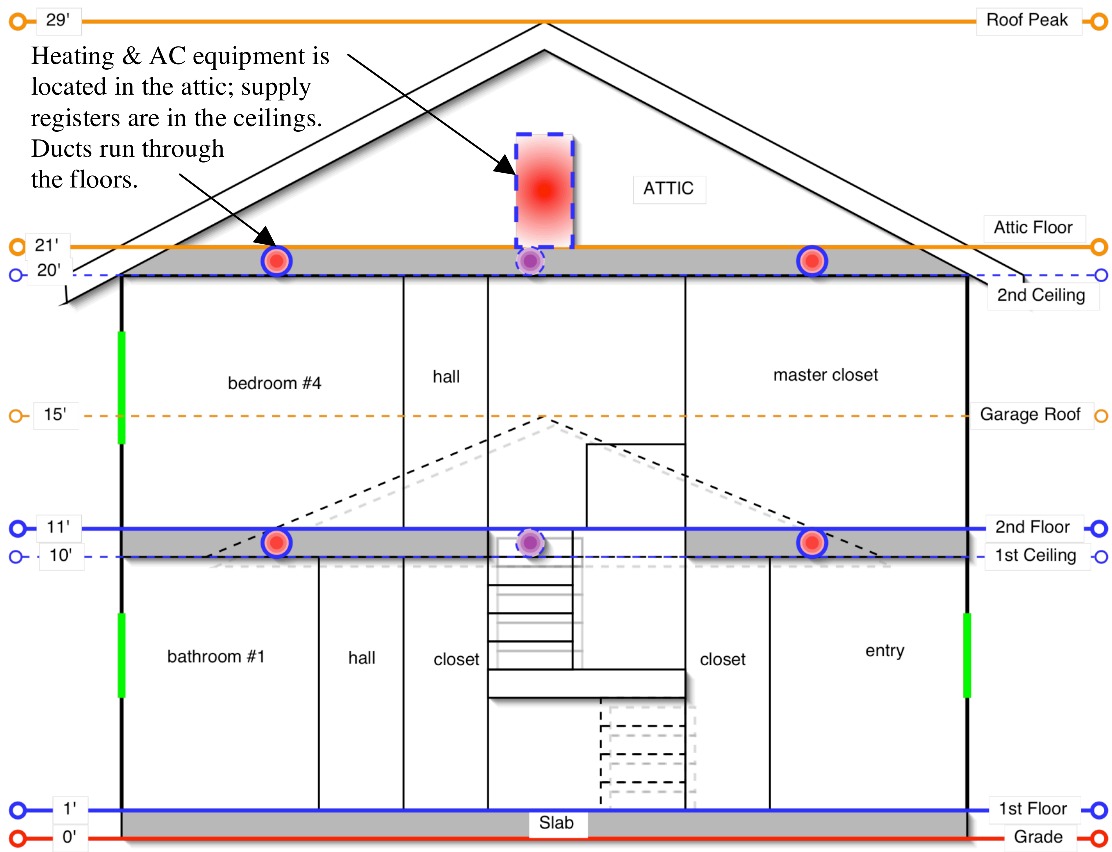
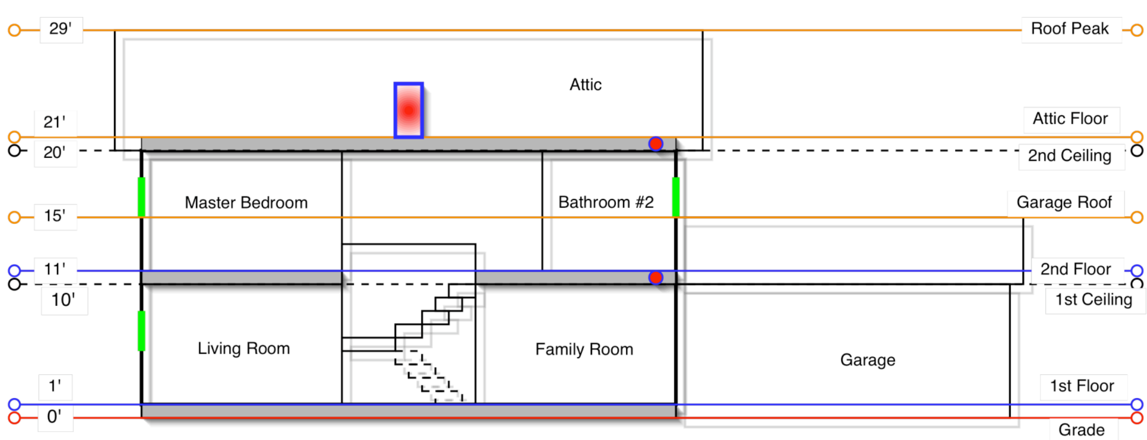


Figure 7. Typical New House: Long Section
(no scale)



8.2 CONTAM Modeling

Once the physical and mechanical characteristics of the virtual new house have been determined, the next step is to use the CONTAM software program to create a computer model of the house in which all parameters that affect building airflow are defined with sufficient accuracy and precision. In this process, we were guided by the assumptions and methods used by Persily (1998) to model a two-storey house in CONTAM; we deviated from those methods when necessary and appropriate.

CONTAM is a publicly-available multi-zone building airflow modeling program developed by the Indoor Air Quality and Ventilation Group (IAQVG), in the Building and Fire Research Laboratory (BFRL) at the National Institute of Standards and Technology (NIST), an agency of the U.S. Commerce Department's Technology Administration. "CONTAMW" is designed to operate on the Microsoft Windows™ operating system. The version of the program used in this study— CONTAMW 2.1—was released in February 2003 (NIST 2003). It is available for downloading from the internet at: http://www.bfrl.nist.gov/IAQanalysis/index.htm

8.2.1 Levels and Zones

A building is represented in CONTAM as one or more *levels,* and one or more *zones*. Levels are defined by their floor-to-ceiling height and floor elevation above grade; *zones* are defined by their area and volume. In our house, levels correspond to floors and zones correspond to rooms; there are three levels (first floor, second floor, attic) and 15 zones, including garage and attic. **Appendix C** shows our house's levels and zones, including detailed dimensions and volumes.

Each zone (room or space) is defined by its level, floor area, volume, pressure, and temperature. Within each zone, the pressure (relative to other zones) and temperature are uniform. Over time, the pressure in each zone can be set to either "variable" (the usual case) or "constant;" e.g., when simulating a blower-door test, one zone is 'constantly' de/pressurized to 50 pascals.

Similarly, each zone's temperature can be either 'constant,' or 'scheduled' by the user. We assume that windows in our house remain closed year-round and the forced-air system maintains a constant indoor temperature of 70 ºF from November through March, and 75 ºF from April through October. Outdoors (outside the building) and any unconditioned zones in the building (our attic and garage) are considered "ambient" zones, whose temperature can vary according to the weather data used.

8.2.2 Airflow Paths and ELA

Once the building levels and zones have been defined, all airflow paths between zones (including outdoors or ambient zones) must be carefully defined, located and sized. Each flow path is defined in terms of the power law; i.e., flow through the path is a function of the pressure difference across it, and a power law coefficient and exponent. Following Persily, our leakage areas are based on the following reference conditions: power law (or discharge) coefficient of 1.0, power law (or flow) exponent of 0.65, and a pressure drop of 4 Pa. From Persily (1998):

> "Airflow elements or paths are described in terms of their effective leakage areas (ELA) at 4 Pa (0.016 in. w.g.). (ELA) of an opening is the area of an orifice with a discharge coefficient of 1.0 that would result in the same flow as that across the opening at a pressure difference of 4 Pa."

The ELA or leakage area of each airflow path can be defined in one of three ways:

- *per item* or “each,” such as a plumbing stack, vent, or duct penetration,
- *per unit length*, such as the perimeter joint around a window, floor, or ceiling, or
- *per unit area*, such as the diffuse leakage through a floor or wall.

Relative distribution of envelope leakage (i.e., the proportion of leakage area in the floor, walls, ceiling, chimney, etc.) is one of many factors that affects building airflow.[36] The single-zone LBL infiltration model (described earlier) accounts for the effect of leakage distribution by incorporating factors R and X. Multi-zone models like CONTAM account for leakage distribution by specifying the elevation of each airflow path. In our virtual house the location of airflow paths is not driven by leakage distribution, but we want to be cognizant of the leakage distribution that results; to that end, we assign each airflow path to one of the following categories from ASHRAE Fundamentals: ceiling, vents, walls, or windows/doors. There is no floor leakage because our house has a slab foundation, but our ceiling leakage is relatively high because of all the ducts running between the house and the attic. **Appendix D** shows the leakage distribution for each of our tightness scenarios.

Appendix D also lists each leakage component, the amount of each component located in each zone, and the ELA value assigned to each component in each tightness scenario. All ELA values are based on those from ASHRAE Fundamentals 2001 (page 26.15) or the Persily report (1998). In the case of “vents” and “exterior ceiling or wall penetrations,” the ELA refers to the leakage area *around* the vent or penetration, and does not include the area of the duct, pipe, or vent.

Notice that the sum of envelope leakage for each scenario in **Appendix D** is 86%—not 100%—of total leakage; the remaining 14% of leakage is in the duct system. Duct leakage is defined by different reference conditions than envelope leakage, so their areas are not additive. Duct leakage has a power law coefficient of 0.6 and a power law exponent of 0.5 (see Eq. 3), and a reference pressure of 250 Pa, which is typical of pressure in the duct system when the forced-air fan operates. Also, while the *percent* of duct leakage is the same for each tightness scenario, the *amount* of duct ELA varies, and must somehow be determined for each scenario. The method we employed was to:

1) ‘Measure’ all envelope (non-duct) leakage to outside by simulating a blower-door test and comparing the ‘measured’ ELA to the targeted sum of ELAs from **Appendix D;** verify that the ‘measured*’* envelope ELA equals *target* envelope ELA for that scenario.[37]
2) From the blower-door equations, calculate the flow that equals the total (envelope + duct) target ELA; from this flow subtract the blower-door flow ‘measured’ for envelope ELA alone; this yields the blower-door flow (m^3/h @50Pa) for duct-only ELA.
3) Divide the duct-only flow in half and in CONTAM, adjust the ELA of both return and supply duct leakage paths until a blower-door simulation confirms that amount of flow through both supply and return duct leakage paths.
4) ‘Calibrate’ total house leakage by conducting a blower-door simulation to confirm that the total targeted (duct + envelope) ELA equals (within 1%) the total ‘measured’ ELA.

Being uncontrolled, duct leakage is seldom balanced between return and supply sides, but we found no evidence that it is consistently higher on one side or the other in residences. Therefore,

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[36] ASHRAE Fundamentals (1985-2001) estimate the relative leakage of ceilings, floors, walls, chimneys, etc.

[37] Within the context of the CONTAM model, ‘measuring’ refers to simulating a field measurement.

we assume leakage in our duct system is balanced (distributed equally between return and supply) and does not affect indoor pressure relative to outdoors.

Appendix D includes only airflow between conditioned and unconditioned (ambient) zones, i.e., it accounts for all *envelope leakage to outside*. Of course all interior airflow paths (between rooms or zones) must also be specified in CONTAM if air is to ‘flow’ within the house. Interior paths include large openings such as doorways, as well as diffuse leakage through walls and floors. As mentioned previously, we define all interior doors as being always open, except bedroom doors, which are scheduled to close eight hours each night, from 10pm–6am. In homes with an exhaust ventilation system and only one forced-air return per storey—which is increasingly common—not only can closed bedroom doors prevent the exhaust fan from providing ventilation air to people sleeping in bedrooms, but closed doors can also significantly affect whole-house air change rates.[38]

8.2.3 Climate

At this point it becomes necessary to decide the location and weather data to use in our analysis. For practical reasons, we limit our analysis to a single location that is both moderate (within the range of U.S. weather), and located in the South and/or West, where most new homes are built. Unfortunately, areas with < 4500 IDD (including the hot arid South/West) need not comply with Standard 62.2, so fast-growing cities like Phoenix and Las Vegas are precluded from our analysis.

We chose Houston Texas not only because it fits our location and weather criteria, but also because anyone who has spent time there will readily accept our premise that windows remain closed and occupants rely on forced-air conditioning. Also, Standard 62.2’s restrictions on ventilation system type by climate do not come into play (see ***Ventilation Restrictions by Climate***), so nothing (official) prevents us from using continuous exhaust ventilation in such a hot and humid climate.[39]

Table 15 demonstrates quantitatively that Houston’s climate is moderate for cities with >4500 IDD. Each table (a–c) sorts the same 11 cities according to a different index of weather severity: weather factor, infiltration degree days, and normalized leakage base. Quoting from LBNL–44479 (Wray et al 2000), normalized leakage base (NL_{base}) is the level of tightness “calculated to make infiltration sufficient to meet the minimum whole-house total ventilation rate required by Standard 62.2P” (P for ‘proposed,’ at that time). In other words, Wray et al determined that in Houston, for example, houses with NL > 0.28 do not need mechanical ventilation. Among this selected range of cities, Houston fits our criteria of having moderate weather *and* being located in the South/West.

[38] With CONTAM it is possible to measure the impact of closed doors on the air changes of each bedroom. However, that analysis is not part of this study, which limits itself to the impact on house air change rates.

[39] According to Standard 62.2, our new 2400 ft^2 4-bedroom house should have a minimum ventilation rate of either 67 cfm or 75 cfm (depending on whether one uses the table or equation, see **Table 11**), and we are “restricted” from continuously operating an exhaust fan larger than (7.5 cfm/100 ft^2 x 24 =) 180 cfm.

Table 15. Comparison of Weather Indicators for Selected Cities

a. Weather Factor (W)
source: ASHRAE Std 136

City	W (AC/h)
Boston	1.07
Minneapolis	0.97
Chicago	0.93
Spokane	0.87
Denver	0.87
Houston	**0.81**
Wash DC	0.76
Portland	0.76
Atlanta	0.75
Tampa	0.75
Raleigh	0.72
average	**0.84**

b. Infiltration Degree Days
source: ASHRAE Std 119

City	IDD (deg F)
Minneapolis	10860
Chicago	8781
Boston	8472
Spokane	7823
Denver	6806
Wash DC	6341
Houston	**6189**
Raleigh	5103
Atlanta	4906
Portland	4860
Tampa	4629
average	**6797**

c. Normalized Leakage base
source: LBNL-44479 (2000)

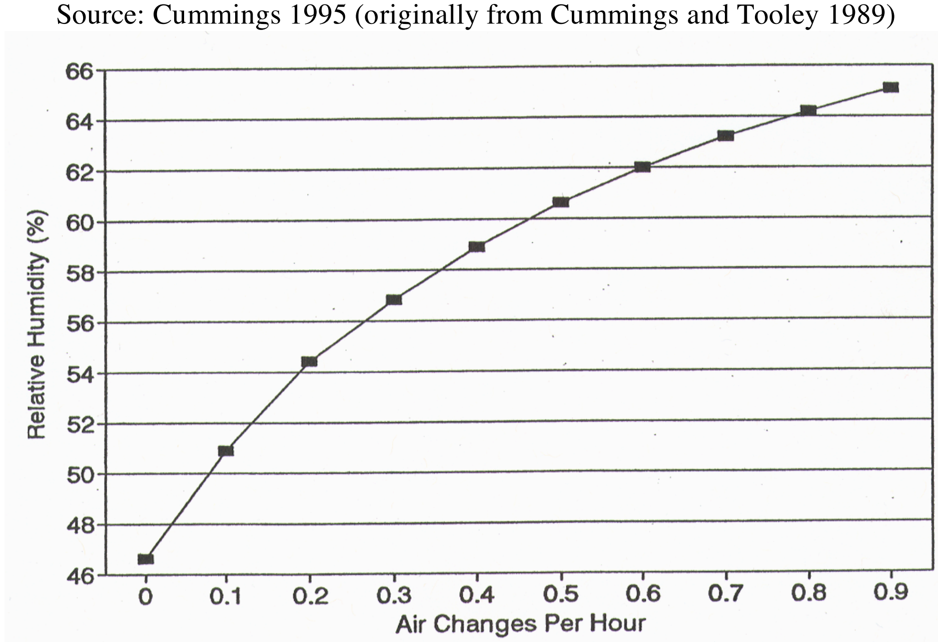
City	NL base
Boston	0.214
Chicago	0.236
Minneapolis	0.246
Spokane	0.263
Denver	0.263
Houston	**0.282**
Wash DC	0.301
Portland	0.301
Tampa	0.305
Atlanta	0.305
Raleigh	0.318
average	**0.276**

Some people will argue that mechanically ventilating homes in hot humid climates (or weather) introduces excess moisture, yet the alternative—uncontrolled infiltration—practically guarantees excess indoor moisture. In fact, outdoor humidity is another reason to build houses as airtight as possible and ventilate them mechanically; only by controlling the air-exchange rate is it possible to control indoor relative humidity (RH) through air-conditioning or dehumidification.

This concept is illustrated in **Figure 6**, which is based on computer modeling of a 1500 ft^2 house in Orlando Florida (which, according to Standard 119–1988, has 4,593 IDDs, compared to Houston's 6,189). The study was conducted by researchers at the Florida Solar Energy Center in 1989 and cited in a subsequent publication (Cummings & Moyer 1995). According to the authors:

> "Most building scientists feel that humidity should be controlled to below 60%, from both a microorganism and comfort viewpoint… At elevated humidity levels, evaporative cooling from the skin slows so that a lower thermostat setting is required to achieve the same thermal comfort ((which) leads to higher energy consumption)."

Figure 8. Summer Indoor Relative Humidity as a Function of Air Change Rate in Orlando FL
Source: Cummings 1995 (originally from Cummings and Tooley 1989)



Indoor relative humidity should be kept below 60% for a number of reasons, including comfort, energy consumption, and to inhibit the growth of allergens (e.g., dust mites), microbes, and mold. Dehumidification is most often achieved (and limited) by the latent capacity of the air-conditioner; when the amount of humid outdoor air entering a home (whether through natural or mechanical means) exceeds the latent capacity of the air conditioner, indoor relative humidity rises. The first, easiest, and most affordable step toward controlling RH in new houses is to control ventilation rates by building a tight envelope and providing mechanical ventilation. **Figure 8** indicates that in Orlando Florida, indoor RH exceeds 60% when the ventilation rate exceeds about 0.5 AC/h.

Now that our climate is known, we can define and schedule the mechanical elements in our house, including the forced-air heating and cooling system.

8.2.4 Mechanicals

In CONTAM, fans and ducts are defined as "duct elements" whose operation can be scheduled. At least one modeling study has concluded that local exhaust fans have negligible impact on house air change rates (Sherman 1997); nevertheless, this study accounts for the impact of intermittent fans. Our house has a 50 cfm exhaust fan in each bathroom and a 100 cfm exhaust fan in the kitchen; these fans are defined in CONTAM as having a "constant volume flow" when on. Following Persily (1998), we assume that the exhaust fan in the downstairs half-bath is never used, but that the exhaust fans in the two upstairs bathrooms operate 30 minutes each day, every day, from 6:30 to 7:00 am. Our kitchen exhaust fan operates one hour each day, from 6–7 pm.

As with many slab-on-grade houses in the South and West, our forced-air equipment is in the attic. Supply ductwork for rooms on the second floor runs through the attic floor (2nd storey ceiling), and a supply trunk extends down through a wall chase to supply ducts in the 1[st] ceiling (2[nd] floor). On each level (storey) there is one centrally-located return ducted to the equipment in the attic. Following Persily (1998), our duct system is measured and adjusted (within CONTAM) until verified to deliver within 10% of the design (target) air supply values, as shown in **Table 16**.

Table 16. Forced-Air System: Design and Delivered Supply Air Flow Rates

	F/A Duct System				Project: NL31_Balanced				Project: NL55_Balanced			
	TARGET				SIMULATED RESULT				SIMULATED RESULT			
	SUPPLY		RETURN		SUPPLY		RETURN		SUPPLY		RETURN	
ZONE	**cfm total**	**m3/h total**	**cfm**	**m3/h**	**m3/h total**	**% of target**	**m3/h**	**% of target**	**m3/h total**	**% of target**	**m3/h**	**% of target**
FIRST LEVEL												
Dining Room	100	170			162	95%			162	95%		
Bathroom #1	50	85			79	93%			77	91%		
Kit/Fam/Hall	150	255	450	764	238	93%	804	105%	238	93%	763	100%
Entry	50	85			82	97%			77	91%		
Living Room	100	170			180	106%			162	95%		
SUM	**450**	**764**			**741**				**716**			
SECOND LEVEL												
Master Bath	50	85			84	99%			84	99%		
Bedrm/Closet #4	90	150			141	94%			139	93%		
Bedrm/Closet #3	100	170			165	97%			163	96%		
Hallway/Stair			540	917			806	88%			768	84%
Bathroom #2	50	85			85	100%			79	93%		
Bedrm/Closet #2	100	170			166	98%			159	94%		
Master Bedroom	150	255			246	97%			229	90%		
SUM	**540**	**914**			**887**				**853**			
SUM, Both Floors	**990**	**1678**	**990**	**1,681**	**971**		**1,610**	**96%**	**1,569**		**1,531**	**91%**

Because each tightness scenario has a different ELA for envelope-only leakage, duct-only leakage, and combined leakage, it was necessary to repeat this tedious duct balancing process for each scenario, two of which are shown in **Table 16**. According to Persily (1998):

"While residential air distribution systems are not typically balanced at this level of detail, this process was needed in the simulations to insure that the intended levels of supply airflow were actually being provided to the individual rooms."

Again following Persily, the forced-air fan is scheduled to operate "a constant fraction of on-time during each month of the year," depending on the outdoor temperatures during that month.

"The system on-time is assumed to be 60% at design conditions, and the relationship between monthly on-time and monthly mean outdoor temperature is assumed to be linear. The on-time fractions determined in this manner were rounded off to the nearest 5 minutes… A schedule was created for each month in CONTAM(W2) such that the forced-air fan is on for the specified duration for each hour of the month."

Table 17 shows our forced-air fan operating schedule, and how it was derived from weather data.

Table 17. Forced-Air Fan Operating Schedule

	Weather for Houston TX			FA fan	On-time
month	HDD	CDD	Net DD	setpoint T	min/hr
Jan	427	15	412	70, heating	20
Feb	298	21	277	70, heating	15
Mar	156	63	93	70, heating	5
Apr	48	147	99	75, cooling	5
May	2	328	326	75, cooling	15
Jun	0	485	485	75, cooling	20
Jul	0	573	573	75, cooling	25
Aug	0	563	563	75, cooling	25
Sep	1	412	411	75, cooling	20
Oct	37	196	159	75, cooling	10
Nov	189	65	124	70, heating	10
Dec	367	25	342	70, heating	15

The remaining mechanical device to be defined in our house model is the exhaust ventilation fan. As explained in **Types of Ventilation Systems**, this thesis limits itself to evaluating the performance of single-port exhaust ventilation systems because they are most likely to be installed in new U.S. houses required to comply with the new Standard 62.2. That section also explains that this thesis only evaluates exhaust ventilation systems that operate continuously, because continuous ventilation is much more effective than intermittent ventilation at reducing indoor pollutant levels.

Our three 'fan scenarios' have already been outlined in **Table 14**. To begin with, we need to know how much ventilation the house receives without a ventilation fan, so we can calculate the amount of ventilation added by a ventilation fan in the other scenarios. Next, we need to test a fan sized according to Standard 62.2, so we can evaluate its ability to provide a minimum 0.35 AC/h.

Standard 62.2 sizes ventilation fans by either of two methods, which are shown in **Table 11** and the equation immediately below it. Using **Table 11**, a 2400 ft^2 4-bedroom house requires 75 cfm (35 L/s) of mechanical ventilation. If instead we use **Equation 9**, Standard 62.2 requires:

$$Q_{fan} = 2400\,ft^2(0.01) + 7.5(5) = 62cfm$$

Put another way, in our new house Standard 62.2 requires a fan size of either 62 cfm or 75 cfm—a difference of about 20%. Because our priority is indoor air quality, we choose the higher rate. Of course, our resulting ventilation rates would be considerably lower if we used 62 cfm.

The third fan scenario is fundamental: test a fan calculated (per house volume) to move 0.35 AC/h. In fact, this option is so obvious you have to wonder why it is not a cornerstone of Standard 62.2. In his 1997 report *Residential Ventilation and Energy Characteristics,* Sherman, who later chaired the Standard 62.2 committee, describes the "spectrum of possible interpretations for Standard 62" (which of course preceded Standard 62.2):

> "The most severe interpretation might be to assume that each room had a minimum of 0.35 air changes at all times; this interpretation would mandate a continuously operating balanced mechanical ventilation system. The most liberal interpretation would only require that the building have the capacity for providing an average of 0.35 ACH; virtually all residential buildings would meet this criterion by having openable windows. The former solution gives no credit to infiltration or natural ventilation, while the latter assumes that occupants are good determinants of indoor air quality and that windows can be opened at any time or weather…
>
> "Our approach is more moderate: to assume that infiltration contributions can be used to provide ventilation, but that the contribution of natural ventilation will be limited to milder weather conditions and that *any whole-house mechanical ventilation system will be sized to meet the 0.35 air change criteria and is run continuously*." (italics added for emphasis).

The same 1997 report models a simple exhaust system with "a continuously operating exhaust fan (that extracts) air from the house at all times at a rate of 0.35" AC/h —i.e., our third fan scenario. To size the ventilation fan to provide 0.35 AC/h, we perform two very simple calculations. First we calculate the building volume, which equals one air change (AC):

$$2400\,ft^2 \times 9\,ft = 21{,}600\,ft^3 / AC \qquad (14)$$

Then we calculate the fan capacity required to move 0.35 air changes per hour;

$$\frac{0.35AC}{hour} \times \frac{21{,}600\,ft^3}{AC} \times \frac{hour}{60\min} = 126\frac{ft^3}{\min} = 126cfm$$

With a continuously-operated exhaust fan, fan size determines the *minimum* ventilation rate, while infiltration determines the total ventilation rate. When infiltration is negligibly low, the exhaust fan contributes its full flow and the ventilation rate equals the fan flow; when infiltration exceeds half the exhaust fan flow, the fan contributes half its flow as additional ventilation, but infiltration contributes the other half, so the total ventilation rate cannot be less than the fan flow.

In other words, when exhaust ventilation is used in new homes, ensuring a minimum ventilation rate of 0.35 AC/h is as simple as sizing a fan to deliver 0.35 AC/h and operating it continuously. The higher the infiltration rate, the higher the total ventilation rate and the lower the efficiency (percent contribution) of the fan; the lower the infiltration rate (whether because of a tight house and/or weak driving forces), the lower the total ventilation rate (to a minimum of the exhaust fan flow) and the higher the exhaust fan efficiency. Yet Standard 62.2 ignores this principle; instead, it sizes fans smaller than 0.35 AC/h and assumes they always contribute their full flow.

In our new house, a 126 cfm exhaust fan ensures a minimum ventilation rate of 0.35 AC/h, while exhaust fans sized according to Standard 62.2 (either 62 or 75 cfm) do not; a 75 cfm fan ensures a minimum ventilation rate of 0.21 AC/h, and a 62 cfm fan ensures a minimum of only 0.17 AC/h. That is our thesis, which will (or will not) be borne out by the results of our CONTAM modeling.

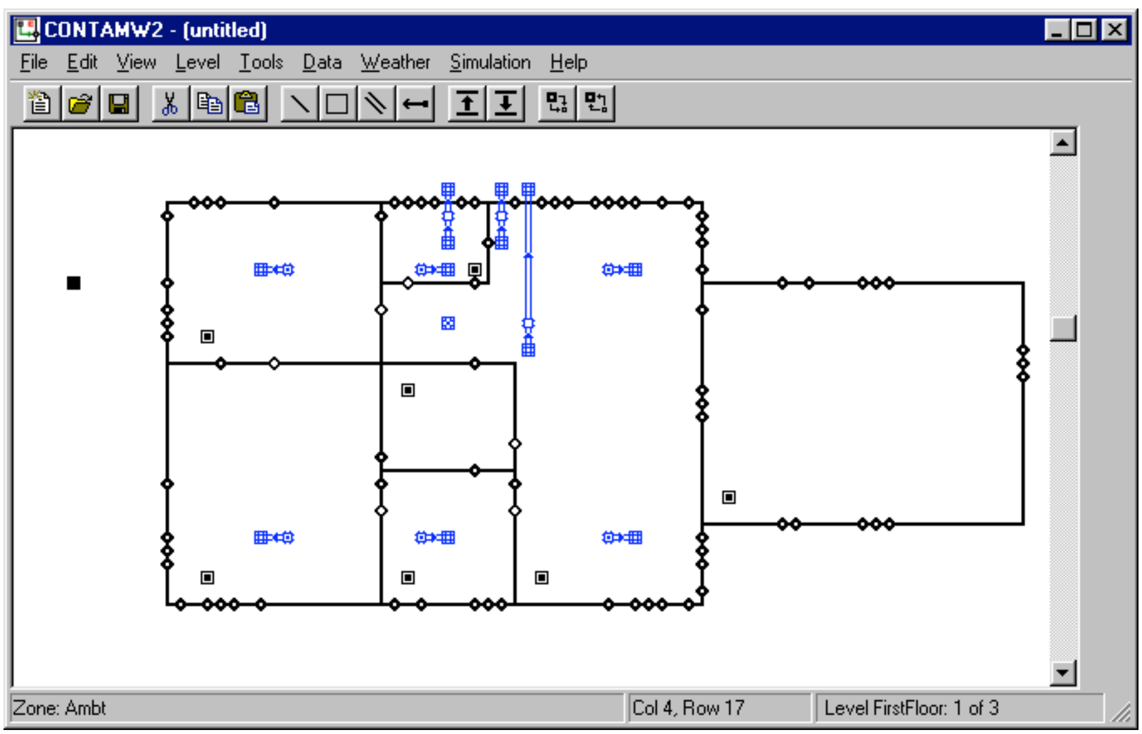
In summary, our first fan scenario (no ventilation fan) represents status quo, without Standard 62.2; our second fan scenario (75 cfm) represents the best-case scenario (in terms of air exchange rates) if the exhaust fan is sized according to the Standard; and our third fan scenario (126 cfm) represents an exhaust fan sized as small as necessary to ensure at least 0.35 AC/h, but no smaller.

8.2.5 CONTAM SketchPad: Model of New House

Figures 9–11 show how our new house looks when modeled in CONTAM's SketchPad.

The SketchPad shows every zone, airflow path, and duct element defined in our CONTAM model; only one level is visible at a time. Each zone (room) on a level is identified by a square (but not solid) black icon; double-clicking a zone icon opens a window with the details of that zone, which can be edited. Diamond-shaped icons represent airflow paths, which are located either in the walls or floor of each level; these airflow paths correspond exactly to those defined in **Appendix D**. The detailed definition of each airflow path can be edited by double-clicking it within CONTAM.

Figure 9. CONTAM SketchPad of New House, First Floor (no scale*)*



Blue rectilinear icons represent duct elements: fans, duct segments, junctions, terminals, grilles. The only duct elements on the first floor are ceiling supply registers in each room and local exhaust fans in the bathroom and kitchen. The following duct elements are on the second floor:

- forced air supply ducts, located in the floor of this level; these supply air to the 1st floor below; (notice that these horizontal duct segments indicate the direction of forced-air flow),
- ceiling registers in each zone (room) that deliver air from supply ducts located in the attic,
- the 2nd floor return grille, located in the ceiling of the central stairwell,
- a local exhaust fan that extends outside from each of two bathrooms, and
- the whole-house exhaust ventilation fan. centrally located near the ceiling of the stairwell.

Figure 10. CONTAM SketchPad of New House, Second Floor (no scale)

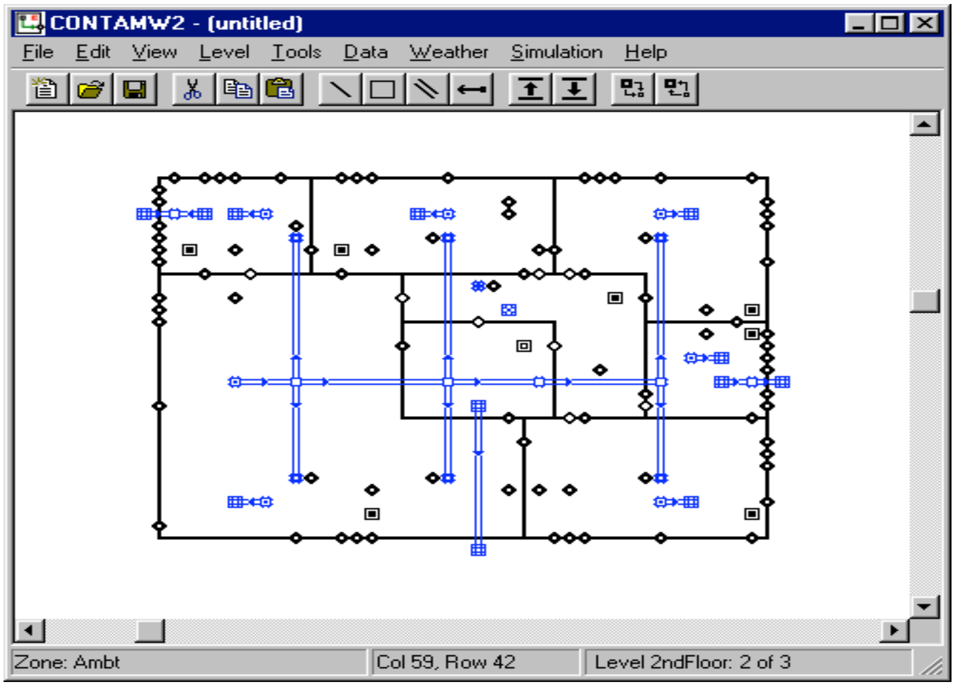
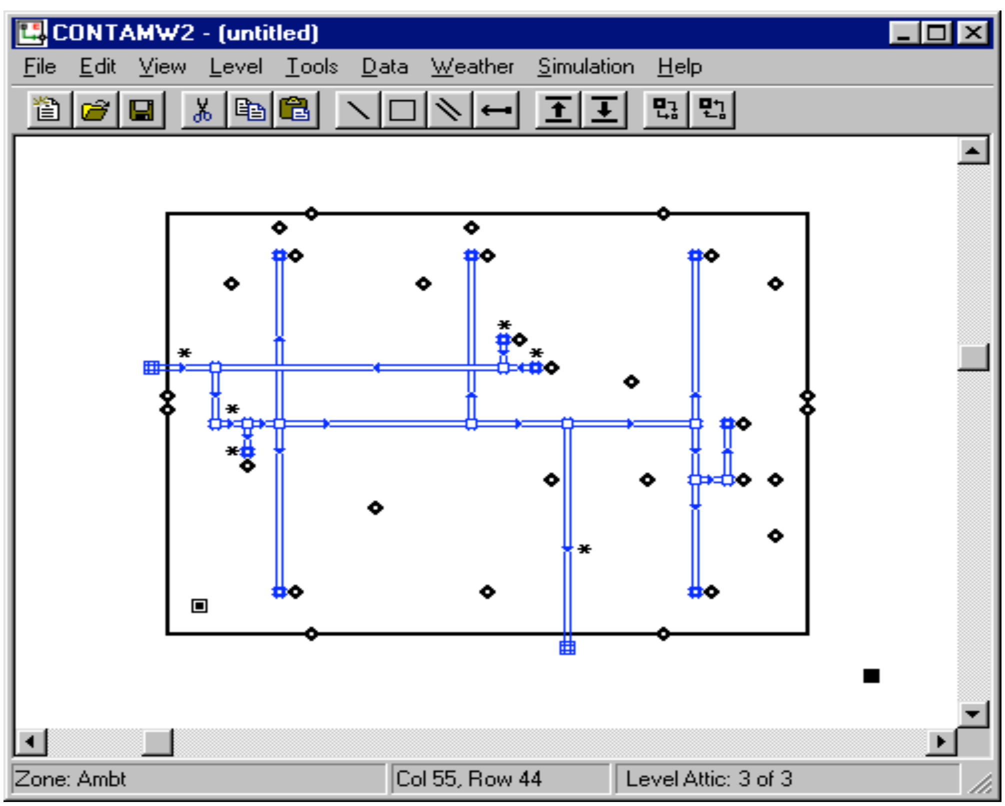


Figure 11. CONTAM SketchPad of New House, Attic Level (no scale)



The attic level contains the following duct elements, each with an asterisk that when clicked within CONTAM yields a description of that element (e.g., 'supply leak,' 'forced-air fan'):

- two return ducts entering the attic from the floors below (upper center of attic floor),
- return duct leak, extending from the return trunk to outside (center of left attic wall),
- the forced-air fan, represented by a very short duct segment (left center of attic floor),
- vertical supply trunk to the first floor (immediately downstream of the forced-air fan), and
- supply duct leak, extending from supply duct to outside (near center of front attic wall).

In the CONTAM SketchPad of our new house, all nine scenarios to be analyzed appear the same; each has the same three levels, 15 zones, 205 airflow paths, and 72 duct elements. The differences between them lie in how each airflow path and duct element are defined for each scenario. Primarily, each airflow path has a different ELA for each tightness scenario (NL23, NL31, NL55), and the exhaust ventilation fan has a different airflow for each fan scenario (V0, V75, V126). Secondarily, the duct system is separately balanced for each tightness scenario.

8.3 CONTAM Simulations

Before performing any simulations with CONTAM, some simulation parameters must be defined. The first decision is whether to measure "steady" or "transient" airflow. A simulated blower-door test is an example of measuring 'steady' airflow for one set of conditions at a single point in time. On the other hand, 'transient' simulations measure airflow that changes over time, in response to changing conditions. When conducting transient simulations, it is necessary to specify dates and times for the simulation to start and stop, and possible to specify the weather data file to be used.

8.3.1 Validation of House Model

The quality of our modeling results depends largely on the quality of our inputs to the model. Therefore, before conducting annual simulations for each scenario, the following steps are taken.

1) **Establish Zero-Flow conditions.** Confirm that all levels and elevations (stack heights) are correctly defined by making all zone and duct temperatures equal (i.e., there is no ΔT, or driving force); make sure all interior doors are open, and all fans are off. Conduct a steady-state simulation and verify that all zone-to-zone airflows are zero (m^3/h).

2) **Verify building ELA, airtightness.** Simulate a blower-door test of house leakage area by setting the pressure in one first-floor zone (room) to 50 pascals; perform steady-state simulation to 'measure' airflow out of that zone. Blower door fan flow converted to ELA should agree to within 1% with the sum of all leakage defined for that tightness scenario.

3) **Ensure local fans and bedroom doors 'operate' according to schedule.** Conduct a transient simulation over the course of a day. Looking at 'Sketchpad' results for airflow, scroll through each timestep to confirm that bath and kitchen fans and bedroom doors operate according to their prescribed schedules (which do not vary from day to day). When a fan operates, a blue vector—representing air flow—is visible at the fan element. When a bedroom door is closed and the forced-air fan runs, a red vector—representing pressure—is visible at the door (because each bedroom has a supply but no return grille); when a bedroom door is open and the forced-air fan runs, the vector is blue (i.e., airflow).

4) **Confirm indoor set-points and forced-air fan schedule.** Besides weather, the only other elements of our model that change during the year are indoor setpoint temperature, which changes twice a year (when the forced-air fan switches from heating to cooling

mode, and back), and the forced-air fan schedule, which changes almost every month (see **Table 18**). Therefore we conduct our simulations in one-month intervals; each month has a project file with the appropriate setpoint temperature and forced-air fan schedule.

8.3.2 Annual Simulation of Air-Change Rates

For each scenario (e.g., NL55_V0), we conduct transient simulations for a full year, using TMY2 (typical meteorological year) weather data for Houston TX (RRDC 2003). Each year is a series of monthly simulations, with each month having the appropriate indoor temperature and forced-air fan on-time determined (see **Table 17**). Interior zone temperatures are 70°F (21°C) during the heating season and 75°F (24°C) during the cooling season. This project has 99 project files: nine scenarios with 11 project files each—one per month, except July and August are combined because they have the same temperature and forced-air fan schedule.

Following Persily (1998), 'simulation' time steps are 5 minutes; this calculation interval captures the effect of forced-air system fan operation and duct leakage on hourly air exchange rates.

We use CONTAM's Post Processing (PP) software module to calculate hourly average AC/h rates for the conditioned space, which does not include the attic or garage. CONTAM PP also creates text files that we convert to Excel files before combining monthly data into an annual file.

8.3.3 Analysis of Results

Once the monthly simulation results are combined into an annual file, we use Excel to determine:

- whole-house air-change rate (AC/h) averaged over each day, week, and month of the year,
- minimum, mean, maximum, and standard deviation of values for hourly, daily, weekly, and monthly average AC/h.
- number and percent of hours, days, weeks, and months per year that are:
    a) under-ventilated (< 0.35 AC/h)
    b) adequately ventilated (0.35–0.70 AC/h), and
    c) over-ventilated (> 0.70 AC/h)
- for the six scenarios with an exhaust ventilation fan—exhaust ventilation efficiency.

The next section presents our results, and it is followed by a discussion of their importance.

9 Results

Table 18 summarizes the AC/h results for all nine scenarios. It includes mean, minimum, and maximum AC/h as well as standard deviation of house air-change rates for each hour, day, week, and month of a typical meteorological year in the moderate climate of Houston TX. To facilitate interpretation and understanding of these results, **Table 14** (from page 49), is reproduced here.

Table 14. Variables Modeled in CONTAM

variable	name	code	description	value
exhaust ventilation fan size	no fan	**V0**	no exhaust ventilation fan	0 cfm
	per 62.2	**V75**	exhaust fan sized per Standard 62.2, Table	75 cfm
	0.35 AC/h	**V126**	exhaust fan sized to deliver 0.35 AC/h	126 cfm
house airtightness level	AKWarm	**NL23**	average of tightest new houses in Alaska	NL 0.23
	Efficient	**NL31**	average of new energy-efficient houses	NL 0.31
	Typical	**NL55**	average of typical new U.S. construction	NL 0.55

Table 18. Summary of Results: Air Changes per Hour
Green shading indicates adequate ventilation. Mean values are the same regardless of averaging time period; they are included for quality assurance.

ventilation scenario	V0	V0	V0	V75	V75	V75	V126	V126	V126
tightness scenario	NL23	NL31	NL55	NL23	NL31	NL55	NL23	NL31	NL55
					Hourly averages				
mean hourly AC/h	**0.19**	**0.25**	**0.40**	**0.32**	**0.36**	**0.51**	**0.43**	**0.47**	**0.59**
min hourly AC/h	0.04	0.06	0.10	0.22	0.23	0.24	0.36	0.37	0.38
max hourly AC/h	0.50	0.65	1.13	0.60	0.73	1.21	0.70	0.79	1.26
standard deviation	0.06	0.07	0.11	0.07	0.08	0.11	0.07	0.07	0.11
< 0.35 AC/h, no. of hours	8634	7882	2712	6446	4190	365	0	0	0
0.35-0.70 AC/h, no. of hours	126	878	5939	2314	4566	7919	8760	8608	7359
> 0.70 AC/h, no. of hours	0	0	109	0	4	476	0	152	1401
total no. of hours	8760	8760	8760	8760	8760	8760	8760	8760	8760
< 0.35 AC/h, % of hours	99%	90%	31%	74%	48%	4%			
0.35-0.70 AC/h, % of hours	1%	10%	68%	26%	52%	90%	100%	98%	84%
> 0.70 AC/h, % of hours			1%			5%		2%	16%
					Daily averages				
mean daily AC/h	**0.19**	**0.25**	**0.40**	**0.32**	**0.36**	**0.51**	**0.43**	**0.47**	**0.60**
min daily average AC/h	0.10	0.13	0.21	0.25	0.26	0.33	0.39	0.40	0.43
max daily average AC/h	0.33	0.43	0.72	0.43	0.52	0.81	0.51	0.61	0.87
standard deviation	0.04	0.05	0.08	0.03	0.04	0.08	0.02	0.04	0.07
< 0.35 AC/h, no. of days	365	350	80	334	135	3	0	0	0
0.35-0.70 AC/h, no. of days	0	15	284	31	230	350	365	365	335
> 0.70 AC/h, no. of days	0	0	1	0	0	12	0	0	30
< 0.35 AC/h, % of days	100%	96%	22%	92%	37%	1%			
0.35-0.70 AC/h, % of days		4%	78%	8%	63%	96%	100%	100%	92%
> 0.70 AC/h, % of days						3%			8%
					Weekly averages				
mean weekly AC/h	**0.19**	**0.25**	**0.40**	**0.32**	**0.36**	**0.51**	**0.43**	**0.47**	**0.60**
min weekly average AC/h	0.14	0.18	0.30	0.26	0.29	0.40	0.39	0.41	0.43
max weekly average AC/h	0.27	0.36	0.59	0.39	0.47	0.71	0.49	0.56	0.79
standard deviation	0.03	0.04	0.06	0.03	0.04	0.06	0.02	0.03	0.06
< 0.35 AC/h, no. of weeks	52	51	7	46	17	0	0	0	0
0.35-0.70 AC/h, no. of weeks	0	1	45	6	35	51	52	52	48
> 0.70 AC/h, no. of weeks	0	0	0	0	0	1	0	0	4
< 0.35 AC/h, % of weeks	100%	98%	13%	88%	33%				
0.35-0.70 AC/h, % of weeks	0%	2%	87%	12%	67%	98%	100%	100%	92%
> 0.70 AC/h, % of weeks						2%			8%
					Monthly averages				
mean monthly AC/h	**0.19**	**0.25**	**0.39**	**0.32**	**0.36**	**0.50**	**0.43**	**0.47**	**0.59**
min monthly average AC/h	0.15	0.20	0.33	0.27	0.31	0.43	0.39	0.41	0.52
max monthly average AC/h	0.25	0.32	0.53	0.36	0.43	0.63	0.46	0.52	0.71
standard deviation	0.03	0.03	0.05	0.03	0.03	0.05	0.02	0.03	0.05
< 0.35 AC/h, no. of months	12	12	1	11	5	0	0	0	0
0.35-0.70 AC/h, no. of months	0	0	11	1	7	12	12	12	11
> 0.70 AC/h, no. of months	0	0	0	0	0	0	0	0	1
< 0.35 AC/h, % of months	100%	100%	8%	92%	42%				
0.35-0.70 AC/h, % of months			92%	8%	58%	100%	100%	100%	92%
> 0.70 AC/h, % of months									8%

To make practical sense of these results, we begin by looking at the amount of ventilation each tightness scenario receives in the absence of a ventilation fan; i.e., we compare the three 'no ventilation fan' scenarios: NL55_V0, NL31_V0, and NL23_V0. Any and all ventilation that our virtual new home receives under these scenarios is a combination of:

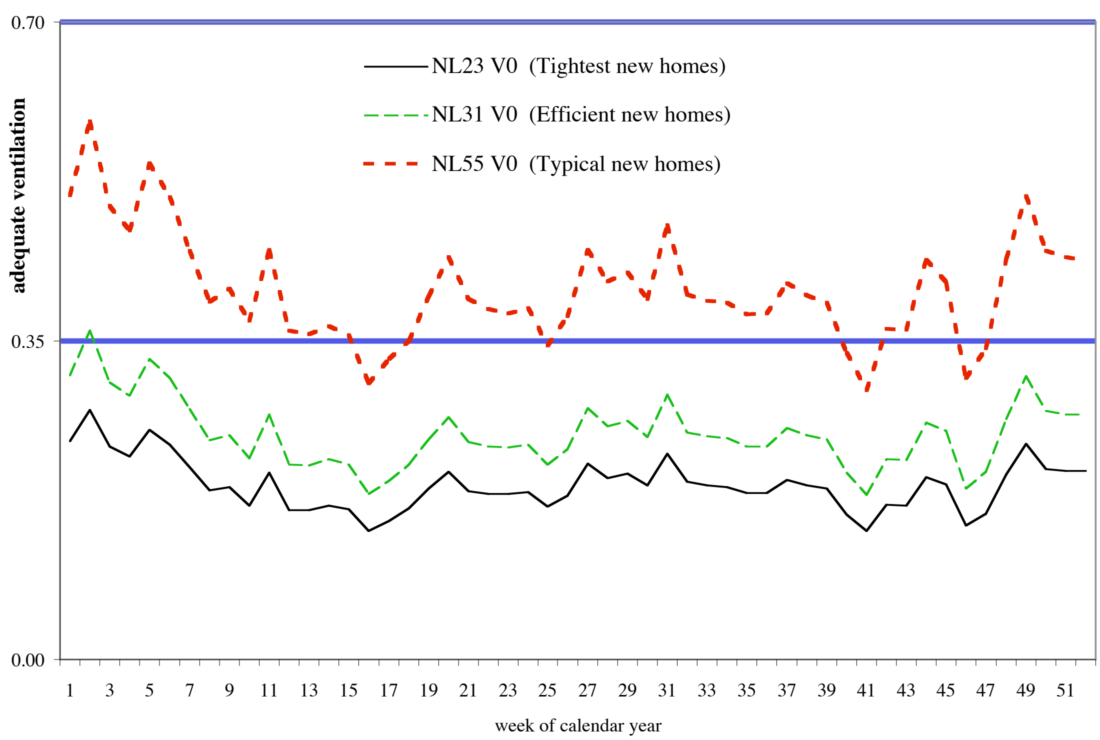
- wind and stack-driven infiltration, which varies according to those driving forces,
- infiltration induced by intermittently operated bath and kitchen exhaust fans, and
- duct system leakage (to and from outdoors) whenever the forced-air fan operates.

The following graphs show AC/h results averaged over every week of the year; weekly averages show more detail and variability than 12 monthly averages, but less than 365 daily averages.

9.1 Weekly Air-Change Results by Ventilation Fan Size

Figure 12 shows AC/h values averaged over every week of a typical metrological year, for each tightness scenario without a ventilation fan. The area between the blue horizontal lines (between 0.35 AC/h and 0.70 AC/h) indicates adequate ventilation. The red dotted line indicates typical new construction, the green dashed line indicates energy-efficient new construction, and the black solid line indicates the tightest houses currently built in the U.S.—in Alaska's AKWarm program.

Figure 12. Weekly Average Ventilation (AC/h) Without a Ventilation Fan



These 'no ventilation' scenario results are extracted from **Table 18** and summarized in **Table 19**. On a weekly average basis, without a whole-house ventilation system, the tightest homes (NL23) never receive adequate ventilation, while typical new homes (NL55) almost always receive adequate ventilation. Energy-efficient homes (NL31) receive adequate ventilation only 878 (10% of) hours, 15 (4% of) days, one week, and 0 months of a typical year in Houston. Looking at **Table 19**, notice how the averaging time period affects the results for each scenario.

Table 19. Periods of Adequate Ventilation without Mechanical Ventilation

averaging period	hours	days	weeks	months
typical new home construction, NL55	68%	78%	87%	92%
energy-efficient new homes, NL31	10%	4%	2%	0%
tightest homes built in Alaska, NL23	1%	0%	0%	0%

Figure 13 shows AC/h values averaged over every week of a typical metrological year, for each tightness scenario with a 75 cfm exhaust fan sized according to Table 4.1a. of Standard 62.2.

Figure 13. Weekly Average Ventilation (AC/h) with Exhaust Fan Sized per Standard 62.2

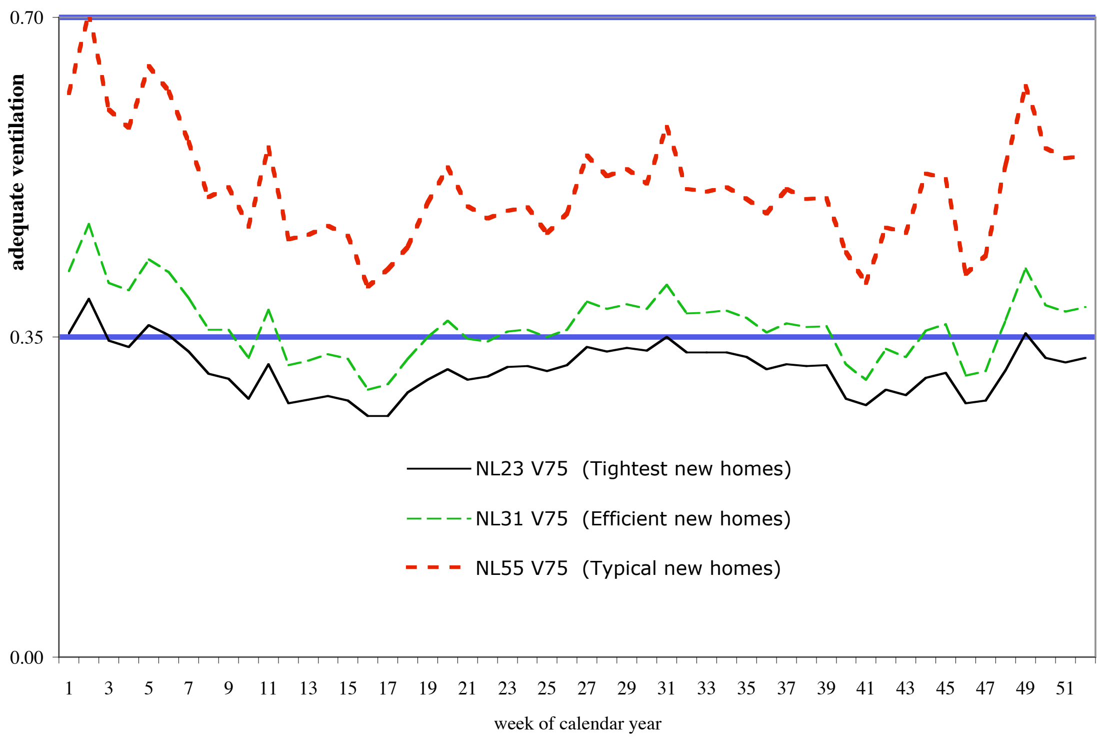


Figure 13 shows that with an exhaust ventilation fan sized according to Standard 62.2, the tightest homes (NL23) seldom receive adequate ventilation, while homes of typical new construction (NL55) always receive adequate ventilation. Energy-efficient homes (NL31) with an exhaust fan sized per Standard 62.2 receive adequate ventilation about half the time (specifically 52% of hours, 63% of days, 35 (67% of) weeks, and 7 (58% of) months). These 'V75' or 'Standard 62.2' scenario results are summarized in **Table 20**.

Table 20. Periods of Adequate Ventilation with Exhaust Fan Sized per Standard 62.2

averaging period	hours	days	weeks	months
typical new home construction, NL55	90%	96%	98%	100%
energy-efficient new homes, NL31	52%	63%	67%	58%
tightest homes built in Alaska, NL23	26%	8%	12%	8%

Figure 14 shows AC/h values averaged over every week of a typical metrological year in Houston, for each tightness scenario with an exhaust ventilation fan sized—according to house volume—to provide the ASHRAE-minimum ventilation rate of 0.35 AC/h.

Figure 14. Weekly Average Ventilation (AC/h) with Exhaust Fan Sized to Deliver 0.35 AC/h

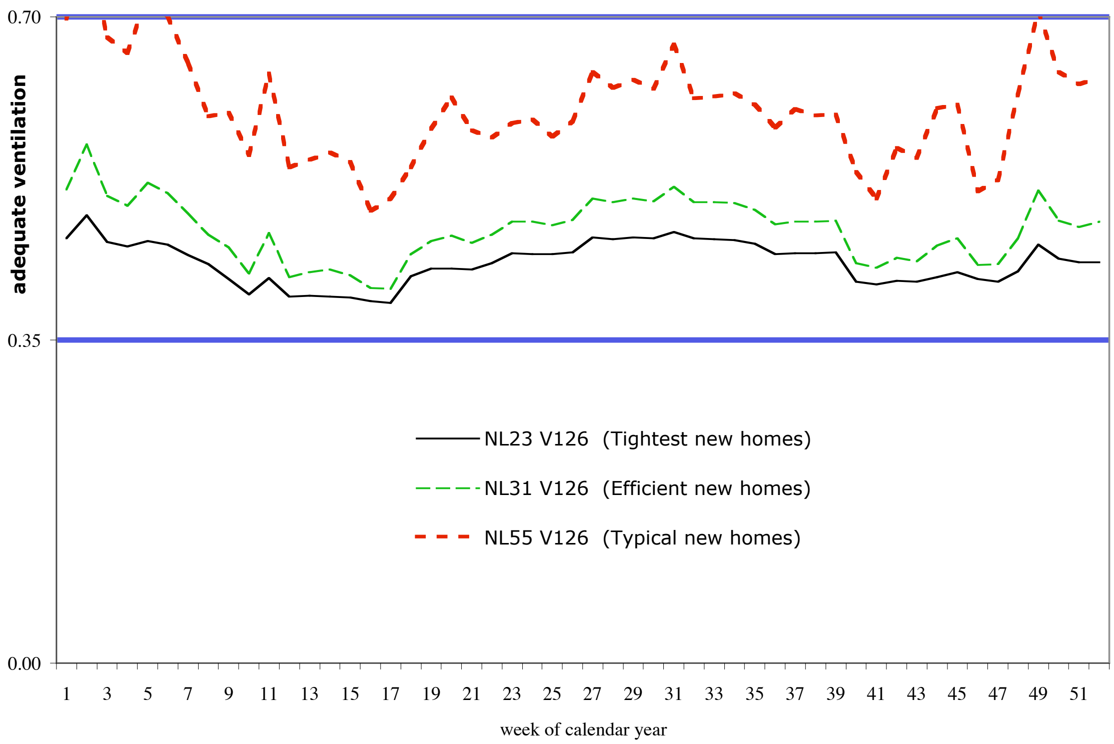


Figure 14 shows that with an exhaust fan sized to deliver 0.35 AC/h, all new homes, including the tightest homes (NL23), always receive adequate ventilation; i.e., they are never under-ventilated, while typically constructed new homes (NL55) are sometimes over-ventilated. These results are summarized in **Table 21**.

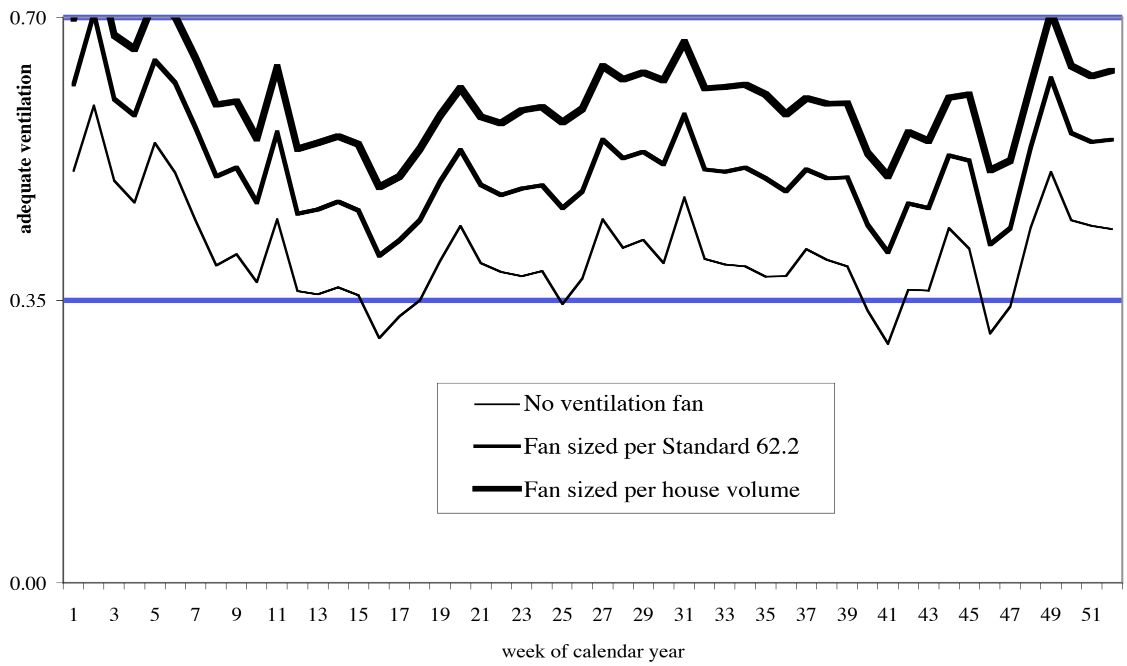
Table 21. Periods of Adequate Ventilation with Exhaust Fan Sized to Deliver 0.35 AC/h

averaging period	hours	days	weeks	months
typical new home construction, NL55	84%	92%	92%	92%
energy-efficient new homes, NL31	98%	100%	100%	100%
tightest homes built in Alaska, NL23	100%	100%	100%	100%

9.2 Weekly Air-Change Results by Type of New Construction

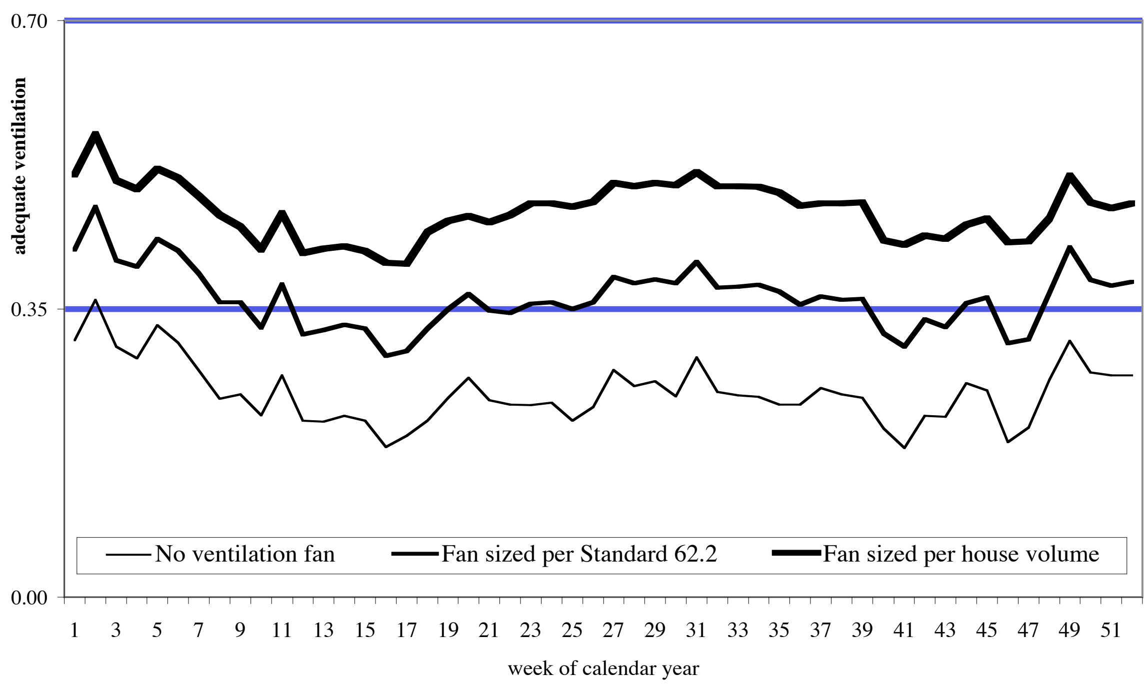
Another way to view AC/h results is to compare ventilation scenarios (V0, V75, V126) for each type of construction. **Figures 15–17** show weekly average ventilation for each tightness scenario. A thin line indicates no ventilation fan, a medium line indicates an exhaust fan sized according to Standard 62.2, and a heavy line represents a fan sized per house volume to deliver 0.35 AC/h.

Figure 15. Weekly Average Ventilation Rates for Typical New Construction (NL55)



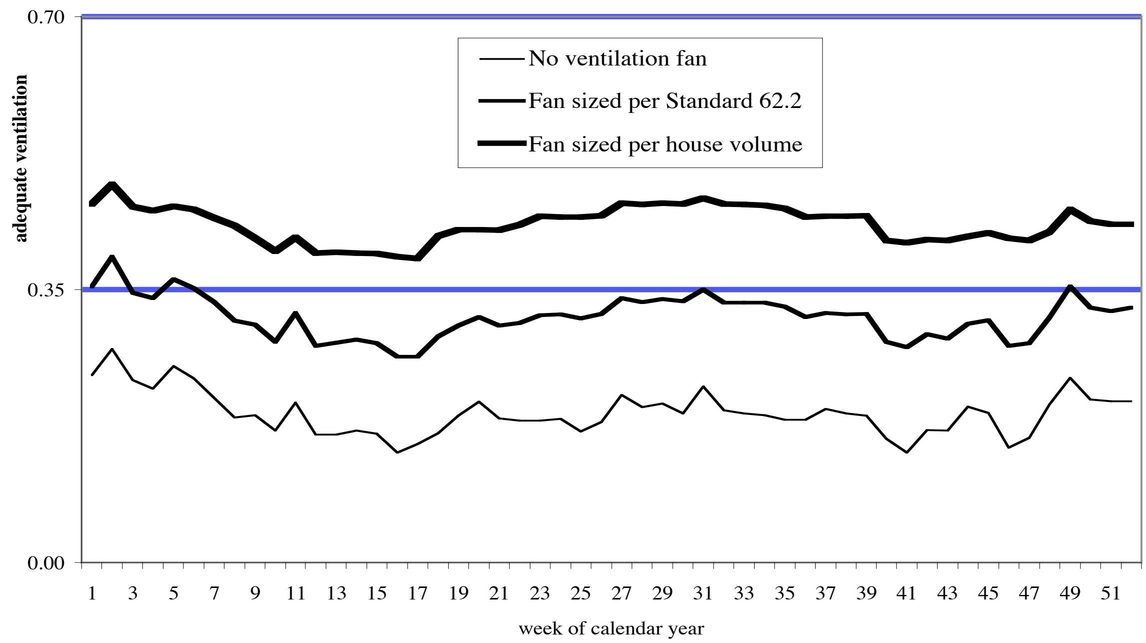
Typical new construction is almost always adequately ventilated *by infiltration alone*, or by a fan sized according to Standard 62.2; the larger fan results in more over-ventilation during winter.

Figure 16. Weekly Average Ventilation Rates for Energy-Efficient New Construction (NL31)



Energy-efficient homes (**Fig. 16**) are almost never adequately ventilated by infiltration alone, but are always adequately ventilated by a fan sized according to 0.35 AC/h. However, an exhaust fan sized according to Standard 62.2 provides adequate ventilation only about half the time.

Figure 17. Weekly Average Ventilation Rates for AKWarm Construction (NL23)



The tightest homes (which need mechanical ventilation most) are always adequately ventilated by a fan sized by house volume, but rarely adequately ventilated by a fan sized by Standard 62.2

9.3 Daily and Hourly Average Air-Change Results

Figures 18–20 present hourly and daily results for all scenarios. Red bars indicate periods of under-ventilation, green indicates adequate ventilation, and yellow bars show over-ventilation.

Figure 18. Hourly Average Air-Change Results for All Scenarios

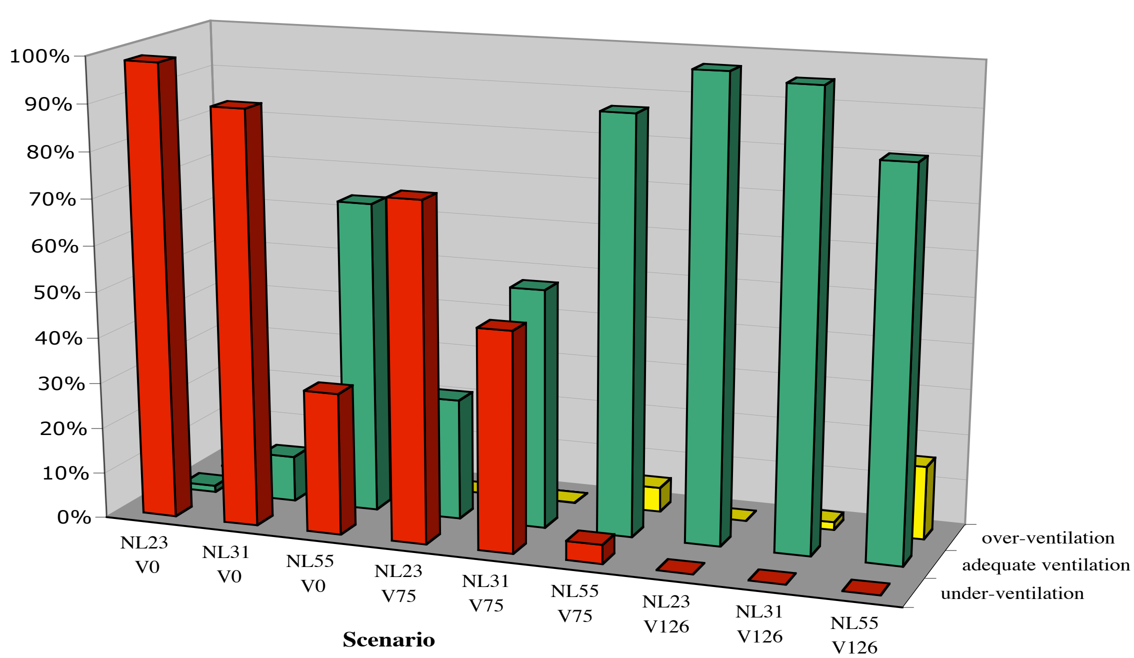


Figure 19. Hourly Average Air-Change Results

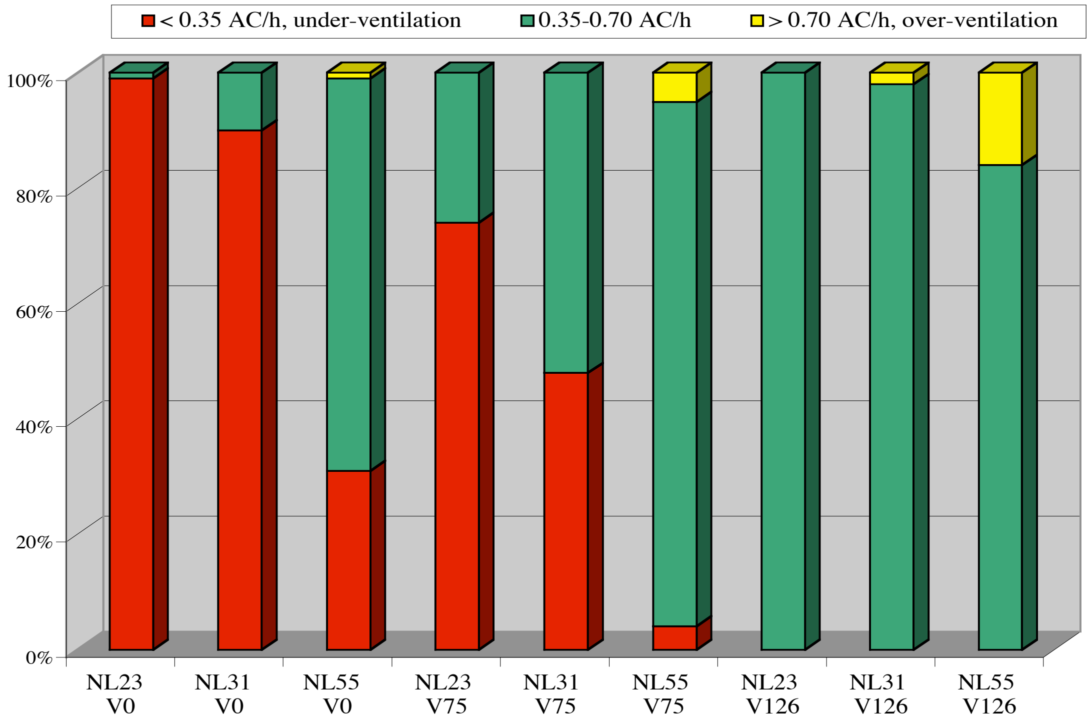
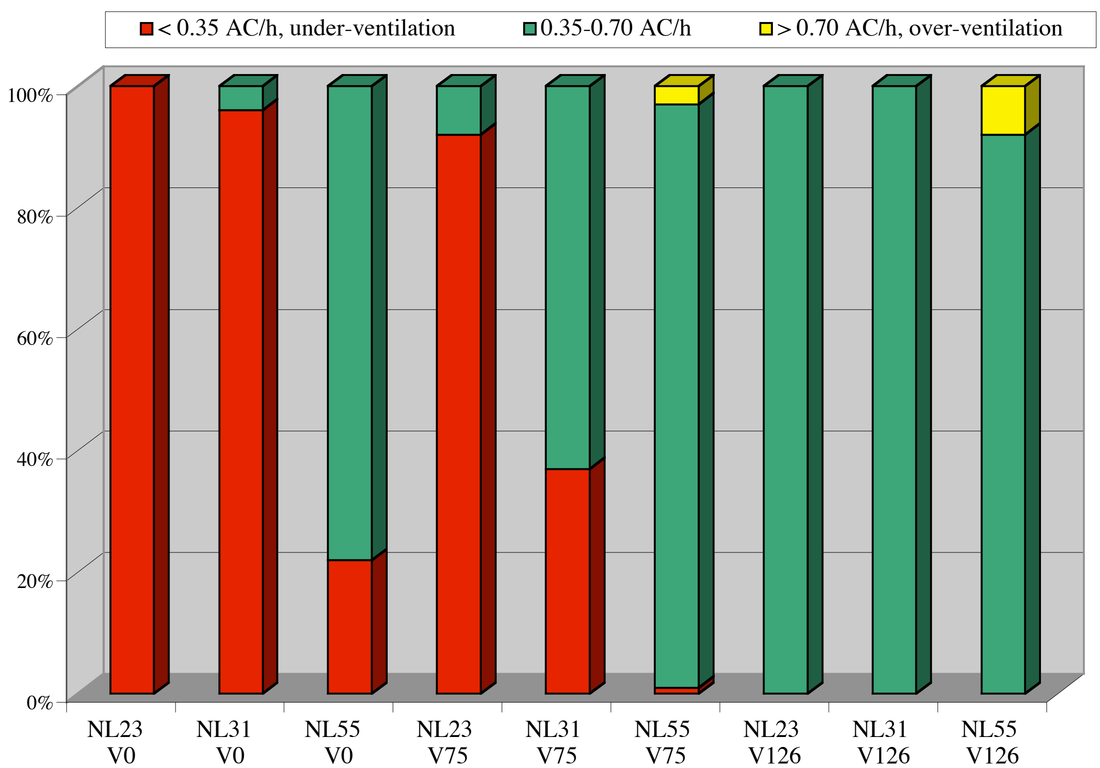


Figure 20. Daily Average Air-Change Results



9.4 Exhaust Ventilation Efficiency

Exhaust ventilation efficiency (**Eq. 13**) is the ratio of the ventilation added by the exhaust fan to the total ventilation rate. **Appendix B** shows examples of ventilation efficiency calculations. Because our exhaust ventilation fans provide a constant flow rate at all times, any variation in exhaust ventilation efficiency is due to changes in the infiltration rate. We calculated exhaust ventilation efficiency for the 22 of 24 hours each day (8,030 of 8,760 hours every year) that the exhaust ventilation fan operated and the bathroom and kitchen spot exhaust fans did not operate.[40] **Figure 21** and **Table 22** illustrate the impact of infiltration on exhaust ventilation efficiency,

Figure 21. Exhaust Ventilation Efficiency
(ventilation added by the exhaust fan ÷ total ventilation rate)

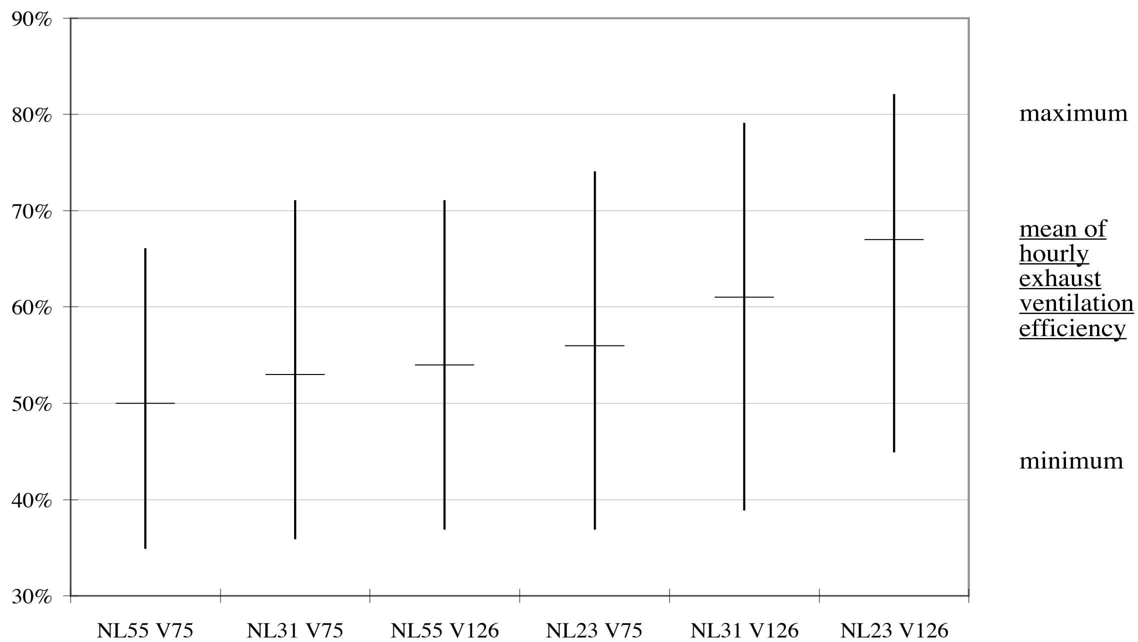


Table 22. Exhaust Ventilation Efficiency
(Scenarios sorted in order of mean efficiency.)

scenario:	**NL55 V75**	**NL31 V75**	**NL55 V126**	**NL23 V75**	**NL31 V126**	**NL23 V126**
maximum	66%	71%	71%	74%	79%	82%
mean	**50%**	**53%**	**54%**	**56%**	**61%**	**67%**
minimum	35%	36%	37%	37%	39%	45%

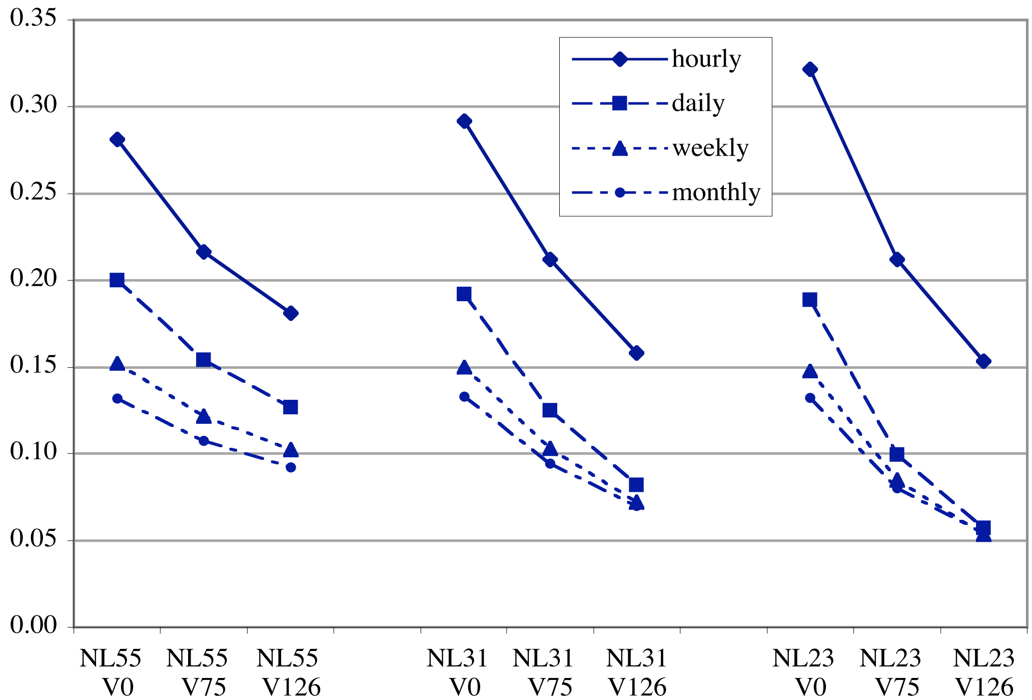
A typically-constructed new house with a 75 cfm ventilation fan—sized per Standard 62.2—has the lowest mean exhaust ventilation efficiency (50%), while the tightest house with the larger fan– sized to deliver 0.35 AC/h—has the highest mean exhaust ventilation efficiency (67%).

[40] This was necessary to avoid including spot fan flow in the calculations of exhaust ventilation efficiency.

9.5 Stability of Ventilation Rates

For scenarios with an exhaust ventilation fan, the stronger the fan is relative to infiltration, the more stable or consistent the ventilation rate, the lower the costs associated with conditioning ventilation air, and the less uncontrolled infiltration the house is likely to receive. This thesis evaluates stability by comparing the *relative* standard deviation (SD) of air exchange values, i.e., the ratio of SD to mean ventilation rate; the lower the relative SD, the more stable the ventilation rate. **Figure 22** and **Table 23** show these values averaged over each hour, day, week, and month.

Figure 22. Relative Standard Deviation of Ventilation Rates



For each tightness scenario, the least stable ventilation rate (highest relative standard deviation) is associated with the lack of a ventilation fan (V0), and ventilation stability increases with fan flow. Between tightness scenarios, notice that the *range* of stability is greater as the house gets tighter. This means that the tighter the house, the easier it is for an exhaust ventilation fan to control ventilation. These and other CONTAM modeling results are discussed more thoroughly below.

Table 23. Relative Standard Deviation of Ventilation Rates

	NL55 V0	NL55 V75	NL55 V126	NL31 V0	NL31 V75	NL31 V126	NL23 V0	NL23 V75	NL23 V126
hourly ave	0.281	0.216	0.181	0.292	0.212	0.158	0.322	0.212	0.153
daily ave	0.200	0.154	0.127	0.192	0.125	0.082	0.189	0.099	0.057
weekly ave	0.152	0.121	0.102	0.150	0.103	0.072	0.148	0.085	0.053
monthly ave	0.132	0.107	0.092	0.133	0.094	0.070	0.132	0.080	0.054

10 Discussion

Before discussing these results, it is worth repeating the conditions on which our analysis is based. We used a multi-zone building airflow model to simulate and calculate whole-house air-change rates in a typical new 2400 ft^2, 4 bedroom, two storey detached house with forced-air conditioning during every hour of a typical meteorological year in a moderate climate in the southern U.S. Windows remain closed because we are evaluating the ability of mechanical exhaust ventilation to provide a minimum ventilation rate. We conducted a parametric analysis varying ventilation fan size and house tightness. These results are most applicable to new homes with exhaust ventilation systems whose fans are sized according to the new ASHRAE residential ventilation Standard 62.2.

We also reiterate that these results are based on the following, often optimistic assumptions:

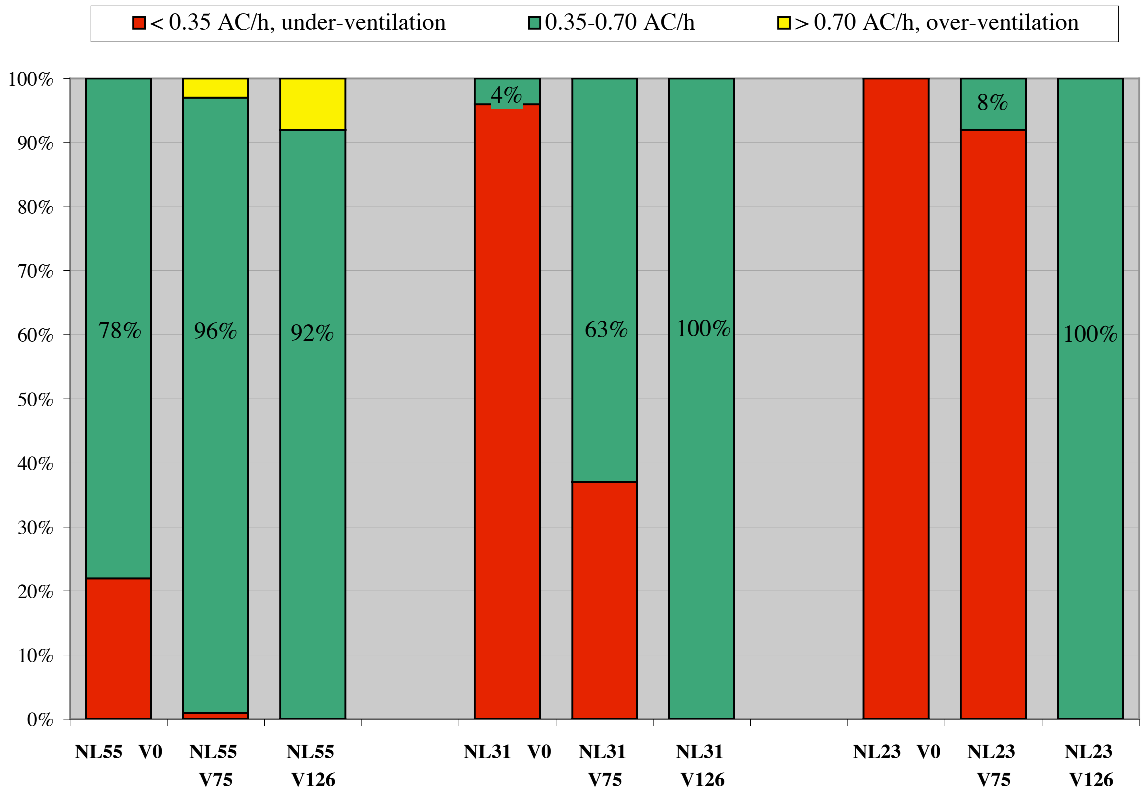
1) Exhaust ventilation should not be used where depressurization is a safety hazard. Any combustion appliances or sources in our house have their own air supply and venting, which are thoroughly sealed from the living space. Ground-source radon is not a concern.
2) Our AC/h results are based on Houston weather data. For homes in milder climates, the impact of weather and infiltration will be lower than presented here, while the impact of uncontrolled infiltration will be much greater on new homes built in more severe climates.
3) When using Standard 62.2 to size ventilation fans, designers can either use an equation to calculate, or a table to look up the cfm value. Both are based on floor area and number of bedrooms, but using the table almost always results in a higher fan flow than the equation. We sized ventilation fans according to the table, but ventilation fans sized according to the equation would result in even lower ventilation rates that those resulting from our analysis.
4) Exhaust fan flows in this study are *delivered* rates. Unfortunately, it is all too common for *delivered* (actual, as-installed) flow rates to be significantly lower than the *nominal* flow rates typically used to select fans. This problem is discussed in more detail below.
5) When selecting airtightness levels to use in our parametric analysis, the 'loosest' level analyzed (NL55) represents the average for typical new construction; therefore, roughly half of new homes built in the U.S. are actually looser than the loosest house in this study. In those homes, exhaust ventilation systems will be even less effective, and uncontrolled infiltration will be even more dominant than our results reported here for NL55 scenarios.
6) The LBNL Leakage Database from which our tightness scenarios are drawn does not know to what extent its measured leakage values include forced-air system leakage to outdoors. We optimistically assume they do, but to the extent that assumption is incorrect, our results overestimate the tightness of—and performance of exhaust ventilation systems in—homes.

We begin our discussion of results by looking at the impact exhaust fans sized by Standard 62.2 have on home ventilation rates, then compare that to fans sized according to house volume.

10.1 Effect of Standard 62.2 on Ventilation Rates

Most homes are built using typical construction techniques, so let's start with the NL55 scenarios. From **Table 18** and **Figure 15**, we see that if our new home is of average tightness, it will receive adequate ventilation 68% of hours, 78% of days, 87% of weeks and 92% of months during a typical year—*even without mechanical ventilation* (scenario NL55 V0). If we go to the trouble and expense of installing and operating an exhaust fan sized according to Standard 62.2, our house is adequately ventilated even more often, but it is also over-ventilated more often. This is illustrated in **Figure 23**, which is **Figure 20** rearranged to facilitate this comparison.

Figure 23. Daily Average Air-Change Results



In typical new construction (NL55, on the left), a fan sized according to the Standard increases the percentage of days with an average ventilation rate of 0.35 AC/h by (96% minus 78% =) 18% of the time. If you don't mind a few days over-ventilation (3%) and a few remaining days of under-ventilation (1%), Standard 62.2 does a fair job of providing ventilation in typical new construction. However, this same house receives adequate ventilation 78% of the time *without a ventilation fan*. Therefore, it is only reasonable to question whether this degree of improvement in ventilation is significant enough to justify the expense of installing and operating the exhaust ventilation fan. By comparison, a fan sized to deliver 0.35 AC/h eliminates any under-ventilation but increases the degree of over-ventilated days to 8%. Apparently, with typical new construction, it's difficult to ensure adequate ventilation without also enduring significant periods of under- or over-ventilation.

In energy-efficient new construction (NL31, in the middle of **Fig. 23**), the situation is much clearer. According to these modeling results, there can be no doubt that:

- Such a house needs mechanical ventilation, because it receives adequate ventilation only 4% of the time without it; or that
- An exhaust fan sized according to Standard 62.2 does a poor job (by any standard), ensuring adequate ventilation less than 2 out of 3 days, *leaving 37% of days under-ventilated*; and that
- An exhaust fan sized to deliver 0.35 AC/h provides adequate ventilation 100% of the time *—with no under-ventilation or over-ventilation.*

If our house in Houston were built like the tightest houses achieved to date in the U.S. (NL23, on the right in **Fig 23**), it would never be adequately ventilated by infiltration, spot fans, and duct leakage alone. Yet with an exhaust ventilation fan sized by Standard 62.2, *it would receive adequate ventilation only 8% of the time*. In contrast, an exhaust fan sized to deliver 0.35 AC/h ensures a constant, reliable ventilation rate of ≥ 0.35 AC/h with no under- or over-ventilation.

10.2 Ventilation Fan Sizing

One of the most important lessons to be taken from these results is that ensuring a minimum ventilation rate in any house—*regardless of its airtightness*—is as simple as sizing a fan to deliver the design ventilation rate (whatever that rate may be) and operating it continuously. The total ventilation rate will rise and fall with infiltration, according to airtightness and the driving forces of infiltration, but the total ventilation rate will never be lower than the ventilation fan flow.

For example, in our 2400 ft^2 house, a fan sized according to Standard 62.2 will guarantee only:

$$75\frac{ft3}{\min}\times\frac{airchange}{21{,}600\,ft3}\times\frac{60\min}{hour}=0.21\ AC/h$$

In **Table 18**, looking at the AC/h values delivered by a 75 cfm fan, we see that the minimum rates during any hour of the year are 0.22, 0.23, and 0.24 AC/h—depending on airtightness scenario; those are 0.01, 0.02, and 0.03 AC/h higher (respectively) than the exhaust fan flow of 0.21 A/C/h. The house ventilation rate is never lower than the fan flow, which in this case is supplemented by a small amount of duct leakage, because our forced-air fan operates at least five minutes per hour. This confirms that even when infiltration is negligible, because there are no driving forces and no other fans operating, the minimum ventilation rate is never lower than the exhaust fan flow.

This analysis of one house shows that an exhaust fan sized according to Standard 62.2 *does not* ensure a minimum ventilation rate of 0.35 AC/h. But what about other new houses? **Table 24** uses the same range of house sizes as in **Table 12** to demonstrate the minimum ventilation rates that fans sized according to Standard 62.2 provide across a range of typical new house sizes.

Table 24. Minimum Ventilation Rates Assured by Exhaust Fans Sized Per Standard 62.2
(Regardless of House Airtightness) (See Standard 62.2's Fan Sizing Equation and Table)

House size			Fan size per Standard 62.2		Minimum Ventilation Rate	
floor area **ft^2**	bedrooms **no.**	volume (ave 9' ceiling) **ft3**	using 62.2's Equation **cfm**	using 62.2's Table **cfm**	using 62.2's Equation **AC/h**	using 62.2's Table **AC/h**
1200	2	10,800	35	45	0.19	0.25
1200	3	10,800	42	45	0.23	0.25
1800	2	16,200	41	60	0.15	0.22
1800	3	16,200	48	60	0.18	0.22
1800	4	16,200	56	75	0.21	0.28
2400	3	21,600	54	60	0.15	0.17
2400	4	21,600	62	75	0.17	0.21
2400	5	21,600	69	75	0.19	0.21
3000	4	27,000	68	75	0.15	0.17
3000	5	27,000	75	75	0.17	0.17
3000	6	27,000	83	90	0.18	0.20
3600	5	32,400	81	90	0.15	0.17
3600	6	32,400	89	105	0.16	0.19

Minimum ventilation rates in **Table 24** range from 0.15 AC/h to 0.28 AC/h, which correspond to 43% and 80% of the minimum 0.35 AC/h, respectively. This analysis shows that ASHRAE Standard 62.2 fails to ensure minimum ventilation rates in new houses that use whole-house exhaust ventilation systems.

11 Conclusion

The physical principles that informed this analysis have been in ASHRAE Fundamentals for over a decade. Members of the Standard 62.2 Project Committee helped elucidate them. So why does Standard 62.2 ignore the relationship between house airtightness and the size of unbalanced fans?

No one can deny that the paradigm shift to mechanical ventilation of U.S. homes is a difficult one. Obviously many builders do not yet accept it, but sooner or later, whether through a desire for quality or the fear of liability, everyone will have to accept responsibility for ensuring indoor air quality in houses that are getting tighter while sources of indoor air pollution remain uncontrolled. The role of ASHRAE engineers and residential building scientists is to provide those homebuilders and residential contractors who are ready and willing to install efficient and effective ventilation systems with the best possible advice, guidelines, and standards regarding how to achieve that goal. Now that Standard 62.2 is approved by ASHRAE and ANSI is a good time to re-examine priorities and get back on the track of communicating building science to the people who are building homes.

The original instincts and recommendations of Standard 62.2's Project Committee were good ones; their assumptions about infiltration in the first Public Review Draft (ASHRAE 2000) were quite conscientious. A simple comparison between that first draft and the final version of Standard 62.2 makes it clear that significant changes were made. In particular, assumed 'infiltration credit' was increased from 1 to 2 cfm/ft^2 floor area, while the mechanical ventilation rate requirement was lowered from 15 to 7.5 cfm per person. Some compromises are inevitable during consensus-based standards-making processes, and this analysis suggests that Standard 62.2 may have succumbed to those. However, this analysis also suggests that if some of the wording in the first Public Review Draft were restored, Standard 62.2 would have a more solid foundation in current building science.

This thesis identifies and demonstrates two problems with Standard 62.2 as it is currently written. First, the Standard assumes new houses always have the same (moderate) level of infiltration, and second, it assumes mechanical fan flow is additive to infiltration when determining ventilation rate. These incorrect assumptions have significant potential consequences for achieving the Standard's goals and more importantly, for the quality of air in houses and health and well-being of occupants. This thesis constructively offers the following suggestions on how to improve the next version of Standard 62.2: *Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings*. The time-frame for suggestions 1), 2), and 3) are short-, intermediate-, and long-term, respectively.

1) Ensure Minimum Air Change Rates

This thesis suggests that Standard 62.2 should, at least, ensure minimum air change rates in homes, because before outdoor air can reach occupants and dilute pollutants, it must first enter the home. We also suggest that while over-ventilation is to be avoided because it is costly and inefficient, prolonged under-ventilation is even more of a concern because it has the potential to impact health.

Currently, Standard 62.2 sizes ventilation fans to deliver much less than the minimum 0.35 AC/h and assumes that infiltration will provide the remainder. In doing so, the Standard contradicts its own premise—that uncontrolled infiltration can no longer be relied upon to ventilate new houses.

The best way to ensure a minimum air exchange rate in new houses when windows are closed is to size the house ventilation fan to move the minimum ventilation rate and operate it continuously. When infiltration is low (whether because the house is tight and/or natural driving forces are low), the fan will deliver its flow and operate more efficiently, without any under- or over-ventilation. When infiltration is high, infiltration will determine the air exchange rate, the ventilation fan will operate less efficiently, the house may at times be over-ventilated but will not be under-ventilated. Any changes to the minimum ventilation rate (by ASHRAE or individual designers) are easily accommodated by simply sizing fans to deliver the new ventilation rate, based on building volume.

2) Encourage Tighter Construction

As currently written, Standard 62.2 doesn't mention the relationship between house tightness and mechanical ventilation performance; even a reader searching for that information would not find it. How can designers begin to understand and integrate principles that are not clearly communicated?

In his 1980 book *Infiltration and Ventilation* Per Olof Nylund of Sweden wrote: "Good ventilation cannot be obtained without tight structures." In 1991 Larry Palmiter of ECOTOPE in Seattle wrote:

> "From an engineering viewpoint, the optimum home is airtight and has a mechanical ventilation system… To make an exhaust-type system function predictably, the house must be tight enough so the pressure induced by the fan at the desired ventilation rate is much greater than the typical naturally produced pressures. In the same way, ventilation produced by balanced neutral-pressure systems is most predictable when the house is so airtight that the natural infiltration is close to zero. As long as there is a significant component of natural infiltration, there will be problems with control and predictability, resulting in either energy waste or inadequate ventilation."

It is much easier to incorporate air sealing in new construction than to tighten a house afterwards. We therefore suggest that Standard 62.2 explicitly acknowledge the impact of building tightness on performance of mechanical ventilation systems, and its own interdependence with ASHRAE Standard 119: *Air Leakage Performance for Detached Single-Family Residential Buildings*. Whether or not either Standard is enforced, they should at least provide appropriate information.

3) Optimize Ventilation Effectiveness

As homebuilders, designers, and contractors assimilate the basics of home mechanical ventilation, they may begin to appreciate its complexities as well. Eventually, Standard 62.2 could include guidance on optimizing indoor air distribution and pollutant removal effectiveness, using either a performance- or prescriptive approach, such as Canada's specification of airflow to each room.

In his 2000 ASHRAE Journal article *Energy Conservation Is an Ethic*, William Coad advocates a new energy/environmental ethical standard for engineers; he wrote:

> "(E)ngineers have the professional responsibility to consider the safety and welfare of the public. Energy and the environment, however, have not been considered more than a design parameter. …(T)hese two issues must be elevated from 'design parameters' to 'moral standards…'

> ”Engineers… are skilled in the art of applied physics necessary to truly understand how to design machinery and systems that preserve the way of life of humanity… while making the most judicious use of the world’s energy resources and creating no adverse impact on the environment.
>
> “(A)s an ongoing obligation, engineers must assume the role of educating their clients, employers, employees, legislators, and the public at large… ASHRAE and other engineering and related societies must become activists in the dissemination of the energy/environmental ethic. The ethic should permeate all publications, papers, seminars, research projects, standards and guidelines.”

Engineers and building scientists have understood for a long time that it is easier to condition and mechanically ventilate a tight house than it is to condition a leaky one. Beyond ensuring that new homes receive adequate ventilation, ASHRAE in general, and Standard 62.2 in particular, have an obligation to enable the homebuilding industry to optimize the efficiency and effectiveness of residential mechanical ventilation systems, whether they (homebuilders) choose to do so or not.

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13 Appendix A. When Is Continuous Depressurization of Homes Safe?

(Source: *Recommended Ventilation Strategies for Energy-Efficient Production Homes: LBNL-40378*, 1998, by J.A. Roberson, R.E. Brown, J.G. Koomey and S.E. Greenberg)

Before installing exhaust ventilation in tight homes, it is important to verify the following circumstances have been met, i.e., that depressurization does not pose a safety and health risk.

EITHER **There are no combustion appliances in the home,**

OR 1) Combustion appliances have separate, sealed supply and exhaust venting, **and**

2) All are free of manufacturing defects or damage from transport, **and**

3) All are properly installed and regularly maintained by qualified personnel, **and**

4) Occupants do not install combustion sources, e.g., natural-draft gas appliances.

AND,

EITHER **There are no fireplaces in the home,**

OR 1) Fireplaces have separate and adequate air supply and combustion venting, **and**

2) Fireplace doors are tested and sufficiently air tight, **and**

3) Fireplace doors are always closed during operation.

AND,

EITHER **The house does not have an attached garage,**

OR 1) Occupants never operate a car in the garage with the garage door closed, **and**

2) There is no air leakage (infiltration) in walls between the house and garage, **and**

3) The door between the home and garage is never open when an auto is idling.

AND,

EITHER **The home is not located in high-radon areas,**

OR A radon-mitigation system is properly installed and continuously working,

OR 1) There are no holes in the foundation, **and**

2) There never will be any cracks in the foundation.

14 Appendix B. Calculation of Exhaust Ventilation Efficiency

Based on the Half Fan Rule, and **Equations 10 and 13**)

infiltration, natural (cfm) (A)	**fan-induced ventilation (cfm)** (B)	**exhaust fan flow (cfm)** (C)	**ventilation, total (cfm)** (D)	**exhaust fan flow ÷ natural infiltration** (C÷A)	**Palmiter's exhaust fan efficiency** (D-A)÷C	**Roberson's exhaust ventilation efficiency** (B÷D)
100	0	0	100	0.0		
100	5	10	105	0.1	50%	5%
100	10	20	110	0.2	50%	9%
100	17.5	35	117.5	0.4	50%	15%
100	25	50	125	0.5	50%	20%
100	37.5	75	137.5	0.8	50%	27%
100	50	100	150	1.0	50%	33%
100	75	150	175	1.5	50%	43%
100	100	200	200	2.0	50%	50%
100	400	500	500	5.0	80%	80%
100	900	1000	1000	10.0	90%	90%
100	1400	1500	1500	15.0	93%	93%
50	12.5	25	62.5	0.5	50%	20%
50	25	50	75	1.0	50%	33%
50	37.5	75	87.5	1.5	50%	43%
50	50	100	100	2.0	50%	50%
50	100	150	150	3.0	67%	67%
50	150	200	200	4.0	75%	75%
50	200	250	250	5.0	80%	80%
50	250	300	300	6.0	83%	83%
50	350	400	400	8.0	88%	88%
50	450	500	500	10.0	90%	90%
50	550	600	600	12.0	92%	92%
50	650	700	700	14.0	93%	93%
50	750	800	800	16.0	94%	94%
50	950	1000	1000	20.0	95%	95%
50	1150	1200	1200	24.0	96%	96%
25	12.5	25	37.5	1.0	50%	33%
25	25	50	50	2.0	50%	50%
25	50	75	75	3.0	67%	67%
25	75	100	100	4.0	75%	75%
25	100	125	125	5.0	80%	80%
25	125	150	150	6.0	83%	83%
25	150	175	175	7.0	86%	86%
25	175	200	200	8.0	88%	88%
25	225	250	250	10.0	90%	90%
25	275	300	300	12.0	92%	92%
25	375	400	400	16.0	94%	94%
25	475	500	500	20.0	95%	95%
25	575	600	600	24.0	96%	96%
25	775	800	800	32.0	97%	97%
25	1175	1200	1200	48.0	98%	98%
25	1975	2000	2000	80.0	99%	99%
25	4975	5000	5000	200.0	100%	100%
10	5	10	15	1.0	50%	33%
10	10	20	20	2.0	50%	50%
10	20	30	30	3.0	67%	67%
10	30	40	40	4.0	75%	75%
10	40	50	50	5.0	80%	80%
10	50	60	60	6.0	83%	83%
10	60	70	70	7.0	86%	86%
10	80	90	90	9.0	89%	89%
10	90	100	100	10.0	90%	90%
10	110	120	120	12.0	92%	92%
10	150	160	160	16.0	94%	94%
10	190	200	200	20.0	95%	95%
10	290	300	300	30.0	97%	97%
10	490	500	500	50.0	98%	98%
10	990	1000	1000	100.0	99%	99%
10	1990	2000	2000	200.0	100%	100%

15 Appendix C. Detail of Zones Modeled in CONTAM

Table A1. Two-Storey House, I-P (English) units

CONTAM ZONES							9.0	ft ceiling			
	zone	**length**	**width**	**area**	**height**	**volume**	**ext wall**	**gross wall**	**window**	**ext door**	**net wall**
	code	ft	ft	ft2	ft	ft3	lin ft	ft2	ft2	ft2	ft2
FIRST FLOOR LEVEL		**40**	**30**	**1,200**							
Kitchen/Family/Hall	kfam			531	9.0	4,779	63	567	72	40	455
Stair	stair	10	7	70	9.0	630					
Bath 1	bath1	7	7	49	9.0	441	7	63	12		51
Dining Room	dining	15	13	195	9.0	1,755	28	252	94		158
Living Room	living	15	17	255	9.0	2,295	32	288	60		228
Entry	entry	10	10	100	9.0	900	10	90	12	20	58
SUM				**1,200**		**10,800**	**140**	**1260**	**250**	**60**	**950**
2ND FLOOR LEVEL		**40**	**30**	**1,200**							
Bedroom 2	bed2	18	10	180	9.0	1,620	28	252	36		216
Bath 2	bath2	10	7	70	9.0	630	7	63	12		51
Hallway/stairwell	hall2	15	10	150	9.0	1,350					
Bedroom 3	bed3			180	9.0	1,620	28	252	36		216
Bedroom 4	bed4	15	10	150	9.0	1,350	15	135	24		111
Master Bath	mbath	10	10	100	9.0	900	20	180	24		156
Master Bedroom	mbed	15	20	370	9.0	3,330	42	378	48		330
SUM				**1,200**		**10,800**	**140**	**1260**	**180**	**0**	**1080**
SUM, BOTH FLOORS				**2,400**		**21,600**		**2520**	**430**	**60**	**2030**
GARAGE(1st LEVEL)	garg	25	20	500	12.0	6,000	70	810	24	148	638
ATTIC LEVEL	attic	40	30	1,200	4.0	4,800	140	240			240

Table A2. Two-Storey House, SI (metric) units

CONTAM ZONES							2.7	m ceiling			
	zone	**length**	**width**	**area**	**height**	**volume**	**ext wall**	**gross wall**	**window**	**ext door**	**net wall**
	code	m	m	m2	m	m3	m	m2	m2	m2	m2
FIRST FLOOR LEVEL		**12.2**	**9.1**	**111.5**							
Kitchen/Family/Hall	kfam			49.3	2.7	135.3	19.2	52.7	6.7	3.7	42.3
Stair	stair	3.0	2.1	6.5	2.7	17.8					
Bath 1	bath1	2.1	2.1	4.6	2.7	12.5	2.1	5.9	1.1		4.7
Dining Room	dining	4.6	4.0	18.1	2.7	49.7	8.5	23.4	8.7		14.7
Living Room	living	4.6	5.2	23.7	2.7	65.0	9.8	26.8	5.6		21.2
Entry	entry	3.0	3.0	9.3	2.7	25.5	3.0	8.4	1.1	1.9	5.4
SUM				**111.5**		**305.8**	**42.7**	**117.1**	**23.2**	**5.6**	**88.3**
2ND FLOOR LEVEL		**12.2**	**9.1**	**111.5**							
Bedroom 2	bed2	5.5	3.0	16.7	2.7	45.9	8.5	23.4	3.3		20.1
Bath 2	bath2	3.0	2.1	6.5	2.7	17.8	2.1	5.9	1.1		4.7
Hallway/stairwell	hall2	4.6	3.0	13.9	2.7	38.2					
Bedroom 3	bed3			16.7	2.7	45.9	8.5	23.4	3.3		20.1
Bedroom 4	bed4	4.6	3.0	13.9	2.7	38.2	4.6	12.5	2.2		10.3
Master Bath	mbath	3.0	3.0	9.3	2.7	25.5	6.1	16.7	2.2		14.5
Master Bedroom	mbed	4.6	6.1	27.9	2.7	76.5	12.8	35.1	4.5		30.7
SUM				**105.0**		**288.0**	**42.7**	**117.1**	**16.7**	**0.0**	**100.3**
SUM, BOTH FLOORS				**216.5**		**593.8**		**234.1**	**39.9**	**5.6**	**188.6**
GARAGE(1st LEVEL)	garg	7.6	6.1	46.5	3.7	169.9	21.3	75.2	2.2	13.7	59.3
ATTIC LEVEL	attic	12.2	9.1	111.5	1.2	135.9	42.7	22.3			22.3

16 Appendix D. Sum of Leakage to Outdoors or Unconditioned Space

Component Category	walls				windows/doors			vents			ceiling			
Envelope Leakage Component	corner, exterior wall	floor to wall joint	ceiling to wall joint	outside wall to ambient	window	sliding glass door	exterior door	bath exh	kitch exh	dryer exh	attic floor	ext clg or wall penes	door to attic	
Zones	**lin ft**	**lin ft**	**lin ft**	**ft2**	**no.**	**no.**	**no.**	**no.**	**no.**	**no.**	**ft2**	**no.**	**no.**	
FIRST FLOOR LEVEL														
Kitchen/Family/Hall	18	63	63	455	6		2		1	1	n/a	2		
Stair											n/a			
Bathroom #1		7	7	51	1			1			n/a	1		
Dining Room	9	28	28	158	2	1					n/a			
Living Room	9	32	32	228	5						n/a			
Entry/Closet		10	10	58	1		1				n/a			
SUM	**36**	**140**	**140**	**950**	**15**	**1**	**3**	**1**	**1**	**1**	**0**	**3**		
SECOND FLOOR LEVEL														
Bedroom/Closet #2	9	28	28	216	3		n/a				180	1		
Bathroom #2		7	7	51	1		n/a	1			70	3		
Hallway/stairwell							n/a				150	2	1	
Bedroom #3	9	28	28	216	3		n/a				180	1		
Bedroom #4		15	15	111	2		n/a				150	2		
Master Bath	9	20	20	156	2		n/a	1			100	3		
Master Bedroom	9	42	42	330	4		n/a				370	3		
SUM	**36**	**140**	**140**	**1080**	**15**	**0**	**0**	**2**	**0**	**0**	**1200**	**15**	**1**	
SUM, Both Floors	**72**	**280**	**280**	**2030**	**30**	**1**	**3**	**3**	**1**	**1**	**1200**	**18**	**1**	
NL 0.55 Typical New Construction, Average														**duct leakage**
Ref Leakage (in2 per)	0.070	0.056	0.070	0.0022	0.60	3.40	1.90	3.10	3.10	2.30	0.026	0.31	2.80	27.0 27.0
Ref Leakage (cm2 per)	1.481	1.185	1.481	0.153	3.87	21.9	12.3	20.00	20.00	14.84	1.81	2.00	18.06	return supply
Component ELA, in2	5.04	15.68	19.60	4.47	18.00	3.40	5.70	9.30	3.10	2.30	31.20	5.58	2.80	**envelope**
Category ELA, in2	**44.79**				**27.10**			**14.70**			**39.58**			**leakage**
Leakage Distribution	**31%**				**18%**			**10%**			**27%**			**86%** sum
NL 0.31 Energy-Efficient Construction, Average														**duct leakage**
Ref Leakage (in2 per)	0.024	0.038	0.024	0.0014	0.30	0.46	0.93	1.60	2.20	1.90	0.020	0.16	1.24	15.0 15.0
Ref Leakage (cm2 per)	0.508	0.804	0.508	0.097	1.94	3.0	6.0	10.32	14.19	12.26	1.39	1.03	8.00	return supply
Component ELA, in2	1.73	10.64	6.72	2.84	9.00	0.46	2.79	4.80	2.20	1.90	24.00	2.88	1.24	**envelope**
Category ELA, in2	**21.93**				**12.25**			**8.90**			**28.12**			**leakage**
Leakage Distribution	**26%**				**15%**			**11%**			**34%**			**86%** sum
NL 0.23 AK Warm Construction, Average														**duct leakage**
Ref Leakage (in2 per)	0.020	0.030	0.020	0.0010	0.25	0.40	0.75	1.00	1.00	1.00	0.014	0.12	1.00	11.0 11.0
Ref Leakage (cm2 per)	0.423	0.635	0.423	0.069	1.61	2.6	4.8	6.45	6.45	6.45	0.97	0.77	6.45	return supply
Component ELA, in2	1.44	8.40	5.60	2.03	7.50	0.40	2.25	3.00	1.00	1.00	16.80	2.16	1.00	**envelope**
Category ELA, in2	**17.47**				**10.15**			**5.00**			**19.96**			**leakage**
Leakage Distribution	**29%**				**17%**			**8%**			**33%**			**86%** sum

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