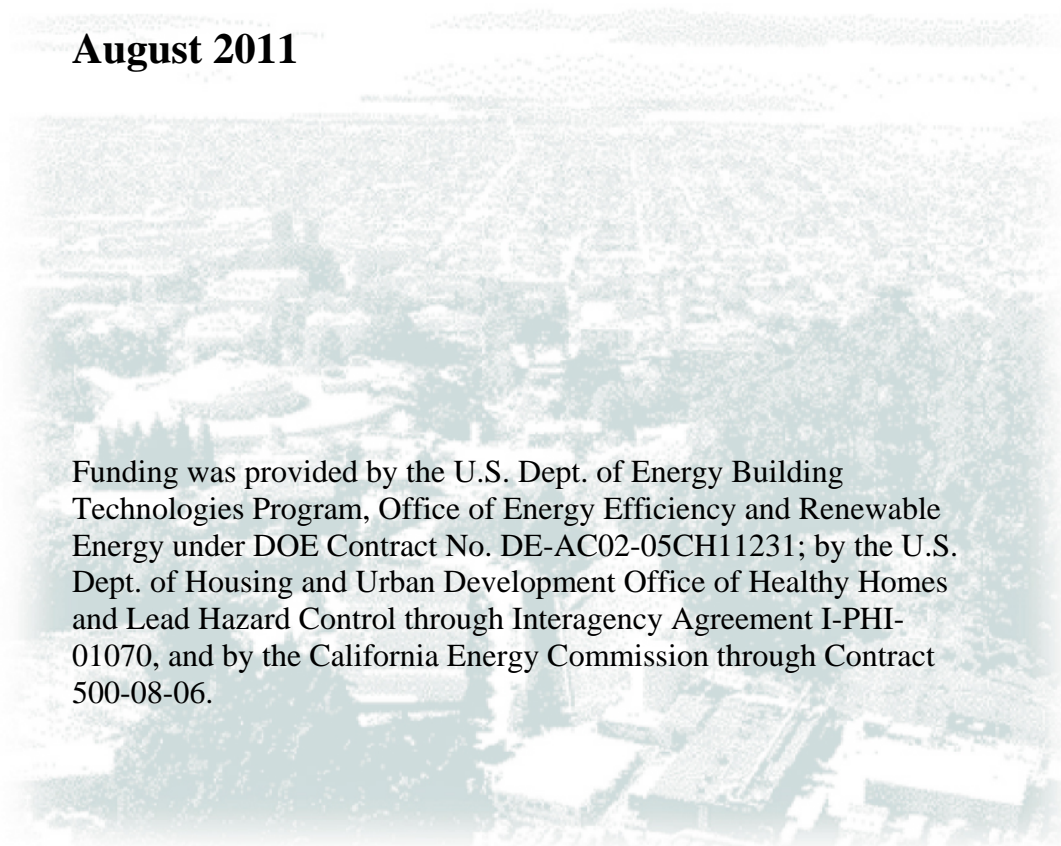# ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY

Equivalence in Ventilation and Indoor Air Quality

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Abstract

We ventilate buildings to provide acceptable indoor air quality (IAQ). Ventilation standards (such as American Society of Heating, Refrigerating, and Air-Conditioning Enginners [ASHRAE] Standard 62) specify minimum ventilation rates without taking into account the impact of those rates on IAQ. Innovative ventilation management is often a desirable element of reducing energy consumption or improving IAQ or comfort. Variable ventilation is one innovative strategy. To use variable ventilation in a way that meets standards, it is necessary to have a method for determining equivalence in terms of either ventilation or indoor air quality. This study develops methods to calculate either equivalent ventilation or equivalent IAQ. We demonstrate that equivalent ventilation can be used as the basis for dynamic ventilation control, reducing peak load and infiltration of outdoor contaminants. We also show that equivalent IAQ could allow some contaminants to exceed current standards if other contaminants are more stringently controlled.

Introduction

Indoor air quality (IAQ) can have a significant impact on occupant health. Indoor pollutant concentrations are determined by building characteristics, ventilation, and outdoor conditions. Although regulations can limit the material loading of certain pollutants, ventilation is currently the key to providing acceptable IAQ. In that sense, it is analogous to heating and cooling being the key processes that provides thermal comfort. Unfortunately, human beings cannot perceive IAQ as easily as they can perceive thermal comfort, especially when IAQ issues have delayed effects. If IAQ was readily perceptible by occupants, buildings could be designed with simple controls allowing occupants to adjust ventilation until the desired IAQ was reached. However, our inability to easily discern the quality of the air around us means we need alternative methods of controlling IAQ.

Instead of using a feedback system or a mechanism analogous to a thermostat, we tend to address the provision of acceptable IAQ by setting standards that buildings must meet. Standards are usually relatively straightforward, for example, establishing maximum or minimum requirements for certain quantities, such as minimum amounts of ventilation or maximum material emission rates. Those limits are almost never based on specific scientific data but rather express expert judgment, with varying levels of conservatism.

In the quest to provide healthy, efficient buildings, there can be significant value in having flexibility in meeting the limits defined in standards, as long as the net impact is the same. For example, in the context of saving energy, if one could provide less ventilation during times of the day when there was a bigger energy penalty (e.g., cold winter nights or hot summer afternoons), then energy (and the money to pay for it) could be saved. This reduced level of ventilation would be compensated for during other times. In a scenario such as this, to "make up for" any contaminant that might fail to meet the appropriate standard for a period of time, we need to establish an *equivalence principle* that allows such trade-offs to be made.

The purpose of this article is to describe equivalence principles for ventilation and IAQ so that these principles can be incorporated into appropriate standards.

BACKGROUND

For most of the existing U.S. housing stock, ventilation is provided by uncontrolled infiltration combined with occupants' use of windows, doors, and bath and kitchen exhaust fans. Sometimes this results in over-ventilation and corresponding excess energy consumption (or introduction of excess outdoor air contaminants, e.g., moisture, small [2.5-micron] particulate matter [$PM_{2.5}$], or ozone if there is no pre-conditioning of outdoor air). At other times, these usual ventilation strategies result in under-ventilation and poor IAQ (Orme 2001). Construction methods for energy-efficient resdiential buildings have created tight building envelopes that can result in under-ventilation (Sherman and Dickerhoff 1994; Sherman and Matson 2002). With the trend toward making new and retrofitted existing homes more airtight, natural infiltration is reduced.

These homes often need mechanical ventilation systems to achieve acceptable IAQ and/or comply with the standards.

The dominant standard for residential ventilation system design is the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 62.2-2010 (ASHRAE 2010b). Standard 62.2 requires source control, including local kitchen and bath exhausts, but a large part of the standard focuses on the continuous mechanical whole-house ventilation. In addition to any assumed infiltration, the standard prescribes the whole-house mechanical ventilation rate given by Equation 1:

$$Q\left[cfm\right] = 0.01 A_{floor}\left[ft^2\right] + 7.5\left(N+1\right) \tag{1a}$$

$$Q\left[\frac{l}{s}\right] = 0.05 A_{floor}\left[m^2\right] + 3.5\left(N+1\right) \tag{1b}$$

where Q is the required ventilation rate, A_{floor} is the house floor area, and N is the number of bedrooms. The size of the house is a surrogate for pollutants from materials intrinsic in the building, and the number of bedrooms is a surrogate for home-occupancy-dependent activities and associated emissions. The specified, required whole-house mechanical ventilation rate is based on the assumption that infiltration contributes 2 cubic feet per minute per 100 square feet or 0.1 liters per second per square meter. Standard 62.2's whole-house ventilation requirement implicitly assumes a constant, additive infiltration rate. Most implementations of Standard 62.2 use constant mechanical ventilation and assume that infiltration is high enough to meet the standard. However, infiltration is highly variable and dependent on the air-tightness of the building envelope as well as on fluctuating conditions that drive infiltration, such as wind and indoor-outdoor temperature differences.

Several national and international standards address IAQ.[1] The standards vary in the quantity of air required and in other details, but they broadly agree regarding how to provide acceptable IAQ and specify the use of mechanical ventilation systems in the same way as ASHRAE Standard 62.2.

There are economic and energy-efficiency rationales for reducing total residential mechanical ventilation and for designing and operating ventilation systems with variable amounts of ventilation airflow (Concannon 2002; Russell et al. 2005). Benefits of reduced and variable mechanical ventilation include reducing energy use during peak load periods, avoiding the intake of outside air during high-pollution events, and reducing the energy used to heat, cool, or dehumidify indoor air.

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[1] Danish Building Regulation, BR10. 2010. http://www.ebst.dk/bygningsreglementet.dk.;
HealthVent. 2011. Health-Based Ventilation Guidelines for Europe, 2011. http://www.healthvent.byg.dtu.dk/,
http://www.healthvent.byg.dtu.dk/;
CEN. 2001. EN1752: Ventilation for Buildings - Design criteria for the indoor environment, 2001.

ASHRAE Standard 62.2 allows for the use of infiltration credits and intermittent operation in residential buildings to accommodate innovative ventilation systems and variable outdoor conditions. However, these ventilation strategies increase the magnitude of fluctuations in indoor pollutant concentrations because they result in periods of reduced and/or no mechanical ventilation. Both weather-induced changes in infiltration and the allowable variability in time-scheduled operation of mechanical ventilation can substantially affect indoor pollutant concentrations. Thus, when ventilation systems are designed to maximize the benefits of infiltration credits and intermittent operation, steps must be taken to ensure that IAQ is not compromised. Designers and policy decision makers need a method to determine how intermittent ventilation and varying infiltration will affect indoor concentrations for both acute-health-impact-relevant and chronic-health-impact-relevant time frames. ASHRAE Standard 62.2 does not directly address these issues.

Ventilation system design and the time variability of infiltration can affect indoor pollutant concentrations in various ways. This study focuses on whole-house ventilation that aims to keep indoor pollutant concentrations at safe levels for avoiding long-term (i.e., chronic) health effects. The two equivalence principles developed in this study are based on preventing long-term, chronic effects. The first is ventilation equivalence, which addresses provision of an equivalent volume of ventilation. The second is IAQ equivalence, which addresses provision of equivalent IAQ.

Throughout this study, we use two key terms: *exposure* and *dose*. Exposure is the concentration in the occupied space, and dose is the amount of pollutant intake that results in the crossing of a biological barrier so that a pollutant is taken up by a target organ. Because we are looking at equivalence principles, we compare the exposure and dose in one circumstance to a base case; thus, our focus is on *relative dose* and *relative exposure*.

Indoor Air Quality and Health

IAQ affects occupant health (Jacobs et al. 2007). Contaminant concentrations in the residential environment are an important contributor to the total air pollutant intake that an individual experiences, as demonstrated in numerous studies (Edwards et al. 2001; Weisel et al. 2005). On average, Americans spend more than two-thirds of their time in residences (Klepeis et al. 2001), and numerous studies have discussed the importance of the indoor environment to cumulative air pollutant intake.

Currently, there are two major groups of air pollutants of concern with well-documented toxicological effects: criteria pollutants, as identified by the 1970 Clean Air Act, and hazardous air pollutants, as identified by the 1990 Clean Air Act Amendment. There is also growing concern that specific bio-accumulating semi-volatile organic compounds in the indoor environment (e.g., brominated flame retardants and phthalates) and ultra-fine particles cause substantial adverse health effects at common environmental levels; however, there are currently insufficient toxicological or epidemiological data to quantify

the associated health damage. The U.S. Environmental Protection Agency (U.S. EPA), the California EPA (CalEPA), the Occupational Safety and Health Administration and several international groups have published health standards or guidelines for long-term average exposure concentrations to protect against cancer and noncancer chronic effects, and for short-term average exposure concentrations to protect against acute heath effects. Acute standards are set at levels that are thought to prevent immediate health effects. These standards are set for 1 hour, 8 hours, or 24 hours. Chronic standards are set at levels that are thought to prevent long-term health effects over a lifetime. These standards are usually set for a time period of 1 year to life and variability in the exposure concentration is ignored. These standards were intended to apply to outdoor pollutant concentrations and have only been applied to a limited extent to identify hazards and risks from indoor concentrations.

Two common methods of determining the prevalence of health impacts from indoor pollutant concentrations are to determine the percentage of households that exceed a specific standard for noncancer effects and to determine the likelihood of cancer incidence assuming a linear dose-response. However, these methods only consider disease incidence in the case of cancer standards, and disease potential in the case of noncancer standards, and do not reflect severity of disease. A consistent, comparative metric is needed for prioritizing pollutants to mitigate indoors, and for comparing the damage from indoor air pollutants to other health burdens. One option for that metric is to use disability-adjusted life years (DALYs) to calculate health impacts as a function of dose. The DALYs metric was originally developed to calculate the burden of disease for the 1993 World Development Report (World Bank 1993).

DALYs are a measure of overall disease damage or burden and incorporate both disease likelihood and severity. DALYs are reported as the equivalent number of years lost as a result of premature death (YLL) or disability (YLD) and offer a way to compare mortality and morbidity.

$$DALY = YLL + YLD \tag{2}$$

The years of reduced health are weighted from 0 to 1, based on the severity of disease, to calculate equivalent years lost. For example, a 5-year illness that reduces quality of life to four-fifths the quality of life in a healthy year is valued at 1 DALY lost.

Several authors have determined the DALYs lost per incidence of specific diseases using the preeminent work of Murray and Lopez (Murray and Lopez 1996a; Murray and Lopez 1996b; Lvovsky et al. 2000; Huijbregts et al. 2005; WHO 2009). Logue et al. (2011b) determined the DALYs lost as a result of long-term (i.e., chronic) indoor pollutant concentrations in the indoor residential environment based on disease incidence models and published values of the DALYs lost per incidence of disease. Logue et al. (2011b) relied heavily on the work of Huijibregts et al. (2005), who determined the DALYs lost per unit intake of many hazardous air pollutants. DALYs provide a convenient metric for making comparisons among the cancer and noncancer effects of chronic (long-term) pollutant concentrations.

VENTILATION EQUIVALENCE

IAQ is usually presumed to be controlled by supplying ventilation. Typical ventilation standards (such as ASHRAE 62) specify prescriptive source control measures as well as whole-building ventilation. Whole-building ventilation is presumed to dilute the remaining contaminants of concern (COCs) to acceptable levels even if those contaminants are not explicitly known.

Many implicit assumptions link a ventilation standard to acceptable IAQ. It is necessary to account for these implicit assumptions and use them – or similar assumptions -- in developing an equivalence principle. One assumption is that ventilation does, in fact, improve IAQ (i.e., that bringing in outdoor air has a net benefit of diluting indoor contaminants rather than a negative effect of bringing in outdoor pollutants). This is embodied in the use of the standard continuity equation:

$$\dot{C} + A \cdot C = S \qquad\qquad \textbf{(3)}$$

where the concentration (C) is related to the air change rate (hr^{-1}) and the source strength (hr^{-1}).

The fact that a time-invariant ventilation rate is specified in typical ventilation standards implies that the standards are not concerned about time-varying concentrations or time-varying sources over a given period. If there is not such a concern, then we can make two simplifying assumptions.

The first assumption is the *equivalent dose* assumption. That is, the standards assume that the key impact of COCs can be expressed by the dose, which is proportional to the time-integrated concentration of those contaminants. We know that, for a variety of toxic substances (e.g., carbon monoxide [CO]), acute exposures are the most important, but the standards assume that these are not the types of contaminants that whole-building (dilution) ventilation is intended to address. We will reexamine this assumption later, but the important metric is the dose. For our purposes, the dose will be proportional to the time-integrated concentration over the entire occupied period (which we can take to be 1 year without loss of generality):

$$dose = k \ \oint o(t)C(t)dt \qquad\qquad (4)$$

where the constant of proportionality, k, depends on the specific contaminant and the function $o(t)$ is zero or one, depending on whether the space is occupied or not. In many real circumstances, occupants may not be exposed for the entire time period because they are not in the building during certain times within the period (e.g., they are away at work). In comparing different ventilation strategies, we presume that the proportionality constant and the occupancy are the same.

The second assumption is the *constant emission* assumption. The standards assume that any COC can be treated as a constant source although, for many contaminants, the source varies over time. The assumption has been that, if we are only interested in dose, we can

use the average source strength instead of the time-varying one. This assumption needs to be reexamined if the COC changes source strength as a function of concentration. This can occur when chemicals (such as formaldehyde) are stored in materials (such as wood products) and allowed to come into equilibrium with the air.

With constant emission and constant ventilation (and the assumption that there is no addition or removal of COCs from any other source or outside), the continuity equation reduces to:

$$C_{eq} = S_{eq} / A_{eq} \qquad (5)$$

where S_{eq} is the unknown emission rate, C_{eq} is the presumed concentration limit, and A_{eq}, which is the only value we actually know, is the air change rate specified in the standard.

We can define the relative exposure, R, as follows:

$$R = C / C_{eq} \qquad (6)$$

The basic principle of equivalent ventilation is that any ventilation pattern that produces the same dose as the standard is equivalent to the standard. In terms of our equations, this is expressed as follows:

$$k \oint C(t) o(t) dt = k \oint C_{eq} o(t) dt \qquad (7)$$

Simply stated, two ventilation patterns are equivalent if they provide the same average exposure to a generic contaminant or over the long term. Because we are using *dose* only in the context of *relative dose*, the constant of proportionality – which would be very important in comparing health effects for different *types* of exposures – appears on both sides of the equation and can thus be set equal to unity without loss of generality.

If one wishes to take into account variable occupancy, equivalence requires keeping track of the contaminant concentration only during the occupied periods. If, however, the space is occupied at all times or the desire is to assume that it is, then ventilation equivalence is satisfied if the average relative exposure is equal to unity.

This principle is embodied in ASHRAE Standard 136 (ASHRAE 2010a), which uses the principle to determine the effectiveness of infiltration at providing ventilation. The principle is also embodied in intermittent ventilation approaches such as in section 4.5 of ASHRAE Standard 62.2 and in the work of Sherman, Mortensen, and Walker (2011b). We give an example of the use of this approach in a real-time application in the section titled "Application of Ventilation Equivalence using Real-Time Relative Exposure," but first we discuss issues related to exposure times in the next subsection below.

Exposure Times

As stated above, the principle of equivalence would allow arbitrarily high contaminant concentrations for short periods of time as long as the average concentration over a longer period of time was acceptable. Clearly this tradeoff will break down at some point. Many of the contaminants found in indoor air have acute (i.e., short-term) concentration limits and, at some peak exposure, these could be violated, making the pattern of short-term exceedances unacceptable.

As an extreme example, consider the limiting case where we have zero ventilation for a time in an occupied space, followed by very high ventilation. In such a case, it can be shown that the maximum time the ventilation system can be off grows sublinearly with the total time, as follows:

$$t_{zero} = \sqrt{2T / A_{eq}}$$

(8)

where T is the total time under consideration and t_{zero} is the time with no ventilation.

There is no upper limit on this. So, if we take the air change rate to be 1/3 air changes per hour (ACH), which is typical of homes and other low-density environments, we could have the ventilation system off for a week or two as long as we had a high ventilation rate for the following year.

Even ignoring oxygen depletion issues, it is not reasonable to assume that occupying a hermetically sealed building for a week would be acceptable because the concentrations of contaminants would become sufficiently high that short-term exposures would be problematic. The ratio of the peak concentration to the average gives us a measure of the peak relative exposure:

$$R_{peak} = \frac{C_{peak}}{C_{eq}} = A_{eq} t_{zero}$$

(9)

In our example, this is approximately a factor of 75. Clearly, that will not be acceptable for some contaminants. Therefore, we must put some boundaries on the use of the equivalence principle to account for this issue.

These boundaries are set by determining the COCs and examining the ratio of acute to chronic exposure limits for these contaminants. Sherman, Logue, and Singer (2011a) have investigated this issue for the contaminants typically found in the (residential) indoor environment. Roughly, they found that for short periods of time (i.e., 1 hour) the concentration of the worst-case contaminant could be allowed to be about 5 times the average concentration.[2]

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[2] The criterion is somewhat different for exposure to particulates, but, as shown in the Discussion section, that issue is moot.

Using Equation 8, we see that, based on the above assumption regarding allowable concentrations, it would be possible to have zero ventilation for about 15 hours, and Equation 7 shows that about a day's worth of high ventilation would be required after that to compensate. Given this result, we conclude that the simple ventilation equivalence principle can be easily used up to durations of approximately 1 day.

If we wish to consider using the principle for periods longer than 1 to 2 days, we need to examine our assumption of zero ventilation. Although one can certainly turn off the mechanical ventilation, that does not mean that the air change rate is actually zero. Other processes provide ventilation, including:

- Exogenous ventilation equipment operates in buildings, including toilet exhaust, kitchen exhaust, economizers, clothes dryers, and other local ventilation.
- Occupant activities and egress, including the opening of doors and windows, can contribute to air change.
- Even the tightest building has some infiltration as natural driving forces interact with building leakage.

If the above processes combined contribute as little as 20% of the desired total air change rate, then the peak contaminant concentration will never reach 5 times the average, and the simple equivalence principle would apply regardless of time frame. In many houses, for example, 20% of total desired air change can be achieved if the air leakage of a house is at least 1 ACH at 50 pascals. The vast majority of both new and existing houses in the U.S. (Sherman and Dickerhoff 1998) are leakier than this value; for them, the simple equivalence principle is appropriate. When the 20% requirement cannot be met by other ventilation-related processes, it could alternatively be met by using reduced rather than zero mechanical ventilation.

ASHRAE Standard 136 could be used directly to determine the contribution of infiltration to meeting ventilation requirements, but one should use it conservatively when determining whether the 20% requirement is met. Sherman (2009) found that the worst day of the year provides only half as much effective ventilation as the annual average, depending on climate. It would be reasonable, therefore, to use only half of the Standard 136 value for determining whether the 20% criterion was met. In the calculation of equivalent ventilation, however, the full value should be used.

Application of Ventilation Equivalence using Real-Time Exposure

The discussion above is best understood in a context where the future is known because it is designed or programmed into the system. For many applications, scheduled events and clock-based control can work quite well. In this section, we consider how one might use a real-time control system to operate the (dilution) ventilation system using the ventilation equivalence principle. To do this, the controller must know the target ventilation, be able to sense the current ventilation, and be able to control a piece of ventilation equipment.

At any one time step, the total air change rate can be calculated as follows, similar to the method used in Sherman (2008):

$$A_i = Minimum(A_{supply}, A_{exhaust}) + \sqrt{A_{background}^2 + (A_{supply} - A_{exhaust})^2}$$
(10)

$$A_{supply} = \sum_{\text{all supply ventilation at step i}} A_{i,supply} \quad \text{and} \quad A_{exhaust} = \sum_{\text{all exhaust ventilation at step i}} A_{i,exhaust}$$
(11)

where "supply" and "exhaust" subscripts indicate the direction of the mechanically induced air change rates and may be made up of the effects of several air-moving devices.

The background ventilation contributed by infiltration and occupant effects could, in principle, be calculated each hour if one knew the appropriate weather conditions and exactly what contaminants were being released because of occupant effects. It is simpler and more practical to treat background ventilation as a constant that is set by envelope air tightness and climate (which assumes that occupant effects are always the same). ASHRAE Standard 136 can be used to estimate the infiltration component of the background air change.

Using either the continuity equations directly or the formulation of Sherman and Wilson (1986), we can find the relative exposure at any time based on the current air change rate and the previous relative exposure:

$$R_i = \frac{A_{eq}}{A_i}(1 - e^{-A_i \Delta t}) + R_{i-1}e^{-A_i \Delta t} \approx R_{i-1} + (A_{eq} - A_i)\Delta t$$
(12)

where Δt is the time step used in the control algorithm. The time step needs to be chosen such that it can reasonably control the system over the time period of interest and gives reasonable precision compared to the operation of exogenous ventilation systems. Typical bathroom, kitchen, or clothes dryer fans will operate for a minimum of about 10 minutes; therefore, a time step of 10 minutes allows reasonable control.

The simple equivalence principle would allow the individual values of ventilation rate and time step to vary as long as the long-term average of the relative exposure was unity. However, we showed earlier that the instantaneous value of the relative exposure should not be allowed to exceed 5, so the control algorithm needs to detect when this happens and turn on whole-house ventilation independent of the long-term average relative exposure.

The most conservative way to use the controller would be to increase the ventilation any time the relative exposure is greater than unity. This would allow cycling of the dilution ventilation equipment to account for incidental ventilation and oversizing of the ventilation equipment.

The principle of equivalent ventilation would, however, allow for periods when the relative exposure was above unity provided there was increased ventilation thereafter, to bring the long-term average down to unity. That requires that the mechanical ventilation system has excess capacity compared to the continuously operating system used as the baseline for the relative exposure. The greater that excess capacity, the more rapidly the system can recover from underventilated periods. The sizing could be estimated using the techniques in Sherman, Mortensen, Walker (2011), but a rule of thumb (details of this derivation are given in Appendix A) that makes sure the recovery can be accomplished quickly is:

$$A > \frac{A_{eq}}{1 - \left(R_{\max} - 1\right)^2 / 16}$$

(13)

where A is the capacity of the mechanical ventilation system, and R_{max} is the largest relative exposure that the controller is designed to allow. Using this rule of thumb, the maximum allowable value of R_{max} is 5, corresponding to the lower limit for the ratio of acute to chronic health standards/ guidelines given in Sherman, Logue, and Singer (2011a).

Any controller that could carry out the above processes would provide acceptable ventilation equivalence. Within that broad constraint, there is a lot of room to optimize other factors such as energy, peak power, exposure to outdoor contaminants, etc. A controller could deliberately turn off the ventilation system using a timer to avoid operation during times of the day with the greatest indoor-outdoor temperature difference and therefore the biggest ventilation energy penalty. It could also detect the operation of other mechanical systems in the home that move air in and out, such as kitchen and bath fans. Figure 1 illustrates the operation of such a controller (from a computer simulation reported in Sherman, Walker and Dickerhoff (2011c) in a tight house dominated by mechanical ventilation airflows, showing response to operation of other fans in the home and the calculated relative dose and exposure. This figure shows how the relative exposure increases linearly when the ventilation system is turned off, how the whole house fan is turned off when other fans can meet the demand for ventilation, and how operation at a single higher airflow rate (in this case $A=1.25A_{eq}$) can give reasonable recovery times from high relative exposure when the system operates on a fixed schedule.
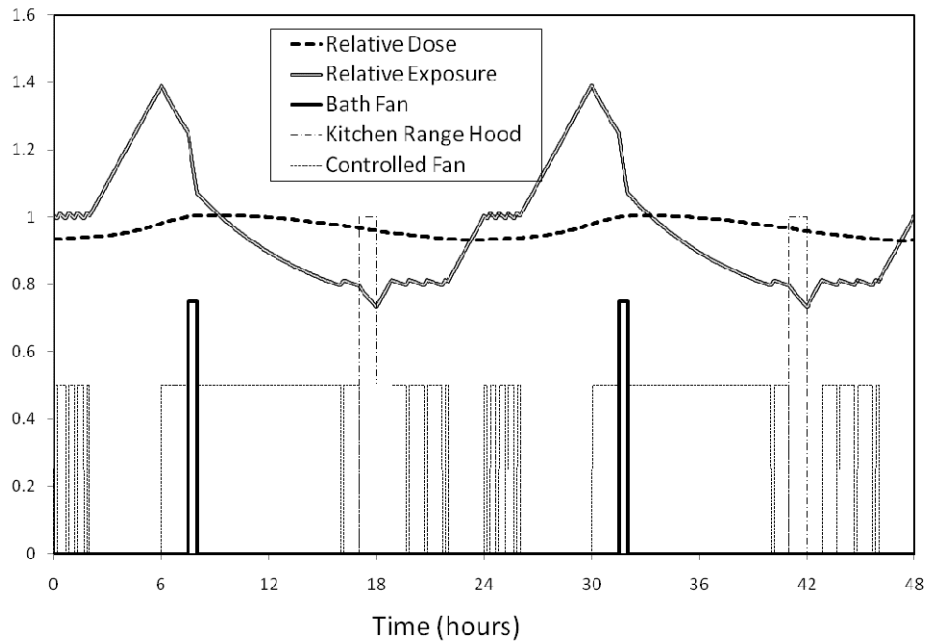
Figure 1. Simulated controlled whole-house ventilation fan (continuous exhaust) and other household fan operation during the winter (hour zero is midnight). The cycling at 0.5 indicates when the ventilation fan operates.

A second case shows results from a controller installed in a home where the operation of kitchen and bath fans by the occupants was recorded and used, together with the measured airflow rates, to calculate the relative dose and exposure shown in Figure 2. In addition, the operation of the home's economizer was recorded The economizer operated in response to indoor and outdoor temperatures during the test period. The figure shows how the economizer ventilated at approximately $10A_{eq}$, leading to rapid reductions in relative exposure. This allowed the whole-house (dilution) fan to be turned off for several additional hours each day.
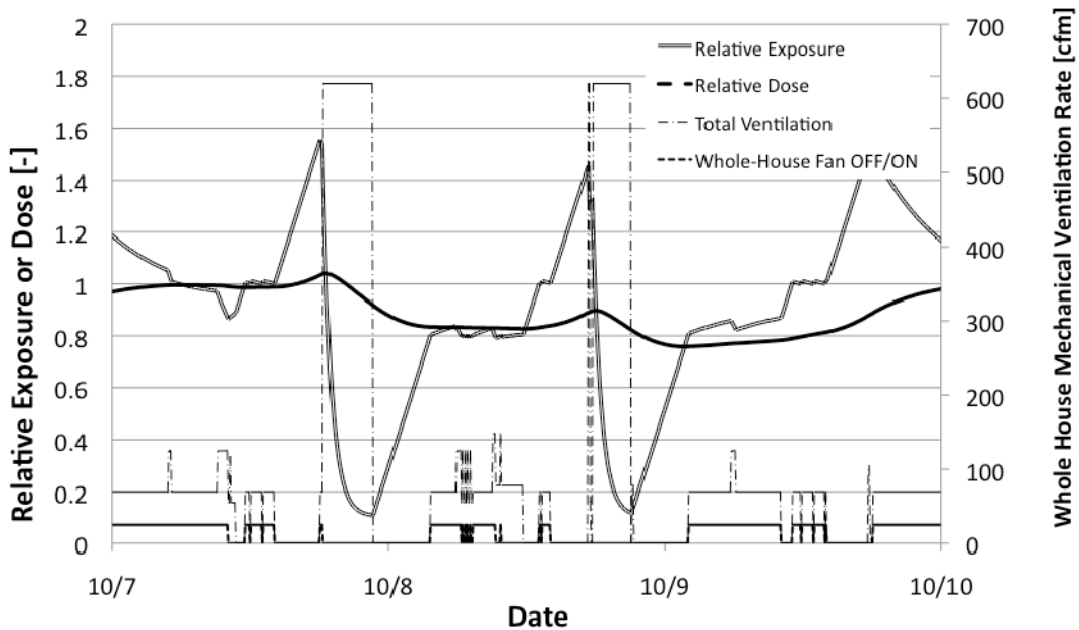
Figure 2. Field Measurements of whole-house, kitchen, and bath fans and economizer operation with calculated relative exposure and dose

INDOOR AIR QUALITY EQUIVALENCE

The equivalent ventilation approach uses exposure to a generic indoor-generated contaminant as the metric to determine the effect of different ventilation scenarios. For ventilation standards, and when one does not know the COCs, this may be the best that one can do. Ideally, though, we would like to determine equivalent indoor air quality based on a health-related metric. To do this would require that we know the contaminants in the indoor environment that are causing significant health impacts and their relative importance.

Logue et al. (2011a) compiled representative statistics for indoor air concentrations of 267 pollutants and identified which of these pollutants exceed health-based chronic and acute standards, identifying nine priority pollutants in the indoor residential environment. Those COCs – eight chemical compounds, along with fine particles, PM2.5, – are listed in Table 1.

Other chemicals were identified as important in some homes, such as radon and tobacco smoke. Radon and tobacco smoke are somewhat different from the other COCs because these two pollutants are usually either present in significant amounts or not present at all. High radon levels are normally addressed independent of whole-house ventilation using dedicated radon control systems. Tobacco smoke depends strongly on individual behavior. Similarly, other compounds may be present in a small number of instances

where they have significant impact, such as 1,4 dichlorobenzene (which is used in moth balls and toilet sanitizers). Prescriptive recommendations on using tobacco products, testing for radon (already recommended for all homes by U.S. EPA), and not using products that contain 1,4 dichlorobenzene and other key COCs may be the way to address these types of COCs that are found in a small number of instances.

Although identifying the contaminants that routinely exceed standards helps identify potential problem sources, it is not sufficient to allow us to develop an equivalence principle. To develop the principle, we need to know how to weight exposure of one chemical relative to that of another in terms of their health impacts. The DALYs metric allows us to make this comparison.

Logue et al. (2011b) applied DALYs to fitted distributions of indoor pollutant concentrations that were representative of the effective exposure concentrations in U.S. homes. Logue et al. (2011b) determined the health impact of the current level of pollutants in the indoor environment to identify which pollutants result in the greatest loss of DALYs because of chronic exposure. Logue et al (2011b) identified three pollutants that cause the majority of heath damage as a result of long-term exposure in the indoor residential environment: $PM_{2.5}$, acrolein, and formaldehyde.

There is large uncertainty about the total damage because of uncertainties in both disease incidence and the damage from diseases. However, much as U.S. EPA does with cancer effects of air toxics, we can use the central estimates to develop a relative weighting. From the central estimates of damage from each pollutant, a unit damage estimate (UDE) value for each pollutant of interest can be determined. This is analogous to the unit risk estimate (URE) values used by U.S. EPA to determine total lifetime cancer risk from a pollutant and will allow practitioners to determine the chronic damage from pollutants directly from measured concentrations.

Table 1 lists the UDEs for the compounds of interest and the chronic (long term average) exposure concentration standards used by Logue et al. (2011a) to identify hazards in the indoor residential environment. These values are combined to determine the damage to residents in a home with the indoor exposure equivalent to the chronic standard. The chronic standard is the National Ambient Air Quality Standard (NAAQS) for the longest available time frame (24 hours for $PM_{2.5}$ and 8 hours for ozone), the reference exposure level for noncancer chronic effects determined by CalEPA, the reference concentration specified for noncancer chronic effects by the U.S. EPA, or the concentration that corresponds to a lifetime cancer risk level of 1 in 100,000 based on the URE values published by U.S. EPA and CalEPA. If multiple standards or guidelines are available for a pollutant, the most health-protective value is reported in Table 1.

Table 1. Indoor Air Contaminants (1 μDALY = 10^{-6} DALYs)			
Compound	*Unit Damage Estimate, UDE* $\left[\dfrac{\mu DALYS}{year*Person}*\dfrac{m^3}{\mu g}\right]$	*Chronic Standard* $\left[\dfrac{\mu g}{m^3}\right]$	*Chronic Standard damage* $\left[\dfrac{\mu DALYS}{year*Person}\right]$
Priority Pollutants			
1,3 Butadiene	0.02	0.06	0.001
1,4-dichlorobenzene	0.03	0.91	0.024
Acetaldehyde	0.3	3.7	0.96
Acrolein	190	0.02	3.7
Benzene	0.08	0.34	0.025
Formaldehyde	6.8	1.7	11.4
Naphthalene	0.47	0.29	0.14
Nitrogen Dioxide	0.70	40	27
PM$_{2.5}$	500	15	7,500
Other contaminants			
Ammonia	0.23	200	46
Ozone	1.4	147	200
Crotonaldehyde	1.02	N/A	N/A

These UDEs or weights can be used to determine the total health impact of an exposure:

$$DALY_{total} = \sum_i concentration_i * UDE_i$$

(14)

This becomes the IAQ equivalence principle: one can set a DALY limit and then allow any combination of contaminant concentrations that keeps the DALY total below the limit.

To use the equivalence principle, we need a limiting DALY value. If we knew the typical source strength of the COCs, we could use the source strengths with the A_{eq} to determine a DALY limit. Unfortunately, those values do not currently exist. Another approach might be to use existing contaminant standards, translate them into DALY values, and then apply the equivalence principle:

$$DALY_{lmit} = \sum_i Standard_i * UDE_i$$

(15)

If we use this approach for the compounds in Table 1, the DALY limit is approximately 8,200 μDALY/p/yr (micro-DALYs per person per year) and is dominated by PM$_{2.5}$. To put this damage level in perspective, we can compare it with some values from Logue et al. (2011b). For example, Logue et al. (2011b) estimate that the current IAQ damage to the population from all sources, excluding secondhand smoke (SHS) and radon, is in the range of 4,000-11,000 μDALY/p/yr, which indicates that the damage attributable to

indoor air is, comparatively, somewhere between the health effects of road traffic accidents (4,000 µDALY/p/yr) and all-cause heart disease (11,000 µDALY/p/yr). The compounds that dominate that total are $PM_{2.5}$, acrolein, formaldehyde, and ozone.

Variations on this procedure can be used by deciding that specific compounds will not be part of the equivalence principle but instead handled through prescriptive measures. If, for example, ozone, radon, and $PM_{2.5}$ were to be handled prescriptively, the DALY limit would drop dramatically to 90 µDALY/p/yr for the other compounds.

Application of Equivalence Principles.

The most straightforward application of the IAQ equivalence principle would be if there were real-time sensors that could determine COC concentrations and change the ventilation rate accordingly. In practice, such real-time sensors do not currently exist.

Another use of the IAQ equivalence principle would be in designing spaces where one could either control the emission characteristics of materials or of source reduction mechanisms (e.g., air cleaning, local exhaust, filtration, etc.). For example, if higher formaldehyde concentrations were necessary, these could be accommodated by enhanced particle filtration and the reduction of unvented indoor combustion (which is a significant source of acrolein, formaldehyde, and $PM_{2.5}$).

Currently the equivalence methodology does not account for the impact of acute exposure (i.e., when concentrations exceed acute standards for short periods). Logue et al. (2011a) identified six pollutants that have been shown to exceed acute standards in homes (chloroform, formaldehyde, NO2, CO, acrolein, and $PM_{2.5}$). Five of these pollutants are primarily linked to episodic activities that have associated task ventilation already, such as range hoods (NO2, CO, acrolein, and $PM_{2.5}$) and showering (a source of chloroform) although there are also emissions from non-vented sources such as ozone reactions with materials, and episodic events like cleaning product use. Task ventilation and source removal should be used to keep these pollutant levels below acute standards when possible and therefore do not need to be addressed in the IAQ equivalency standard. Formaldehyde has substantial material emissions and concentrations in homes and may exceed acute standards because of these emissions alone. When applying the IAQ equivalency standard, steps should be taken to keep formaldehyde concentrations below acute standards or to expand the IAQ methodology to account for the health damage associated with those acute exposures.

DISCUSSION

The IAQ equivalence principle is directed more at protecting health than is the ventilation equivalence principle, but, until significantly improved sensors and data sources are developed, the IAQ equivalence principle is impractical to use operationally. It does, however, provide a way for researchers and policy makers to understand the effects of various IAQ options.

In the context of a ventilation standard (e.g., ASHRAE Standard 62), ventilation equivalence is a powerful tool for saving energy and improving IAQ by shifting ventilation to more desirable times. Although ventilation equivalence assumes that COCs are reasonably constant it is, at this time, the only practical approach that can be used. Ventilation equivalence definitions, methods, and restrictions could be incorporated in standards (such as ASHRAE 62) to allow the use of flexible ventilation systems that can address issues of energy use and peak demand as well as avoidance of events where outdoor air pollution levels are high.

In cases where some COCs are from outdoor sources (such as in NAAQS nonattainment zones), equivalent ventilation can help improve IAQ by allowing the dilution of indoor sources to take place at times when outdoor sources may be less. Such an approach is qualitative with respect to the outdoor sources. The IAQ equivalence principle would allow a quantitative approach in which exposures from indoor and outdoor sources could be traded off.

It is interesting to note that the level of protection afforded by the standards differs for concentration limits of different compounds. There are six orders of magnitude in the DALY cost of meeting the different standards. There are, of course, many other reasons why the levels in the standards might be set, e.g., practical issues or uncertainties in test procedures or toxicological data. From an overall IAQ perspective, however, we would worry less about failing to meet the standards for low-damage compounds than the standards for compounds that do greater damage. This is an area for further research.

Particles

Particles with diameters less than 2.5 microns ($PM_{2.5}$) have a special place in this discussion. From the Logue et al. (2011b) findings, we see that the largest DALY cost to the population from indoor contaminants comes from $PM_{2.5}$. Indoor concentrations of $PM_{2.5}$ are a function of both indoor and outdoor sources. Whether indoor or outdoor sources are the dominant contributors to indoor concentrations is a function of home air exchange rate, particle entry path, home location, and indoor sources. Wiesel et al. (2005) measured indoor and outdoor $PM_{2.5}$ concentrations in 100 homes in each of three cities – Los Angeles CA, Houston TX, and Elizabeth NJ – as part of the Relationships of Indoor, Outdoor, and Personal Air Study. The results showed that roughly half of the homes had higher $PM_{2.5}$ concentrations indoors and half had higher concentrations outdoors. From this, we can conclude that, for many homes, simple ventilation will increase exposure to the most significant contaminant rather than decrease it.

This suggests that exposure to particles should be controlled through a combination of task ventilation for indoor combustion sources and filtration rather than through whole-house ventilation. Basic ventilation rates should be based on other COCs – those that are principally indoor sources – such as formaldehyde and acrolein.

Currently, most ventilation standards do not require filtration of particles from air, except to protect heating, ventilation, and air conditioning equipment from fouling. Reducing $PM_{2.5}$ through filtration would substantially reduce DALYs lost due to indoor $PM_{2.5}$ exposure.

Secondhand Smoke and Radon

SHS and radon pose significant risks in only a small number of households. In those homes, source control is the most effective means of reducing risks. Because of that, the analyses above did not include SHS and radon risk. However, in situations where these contaminants are present, they can pose a significant risk. Nonsmokers who live in smoking households, for example, are typically subject to about 10,000 µDALY/ p/yr, which is likely greater than the health impact from their exposure from all other compounds in the indoor air. Radon represents an annual population average health damage of 130 µDALY/ p/yr for nonsmokers. These values do not address the direct effect from smoking, nor do they address the interactions between smoking and radon exposure. In homes with these risks factors, removing the source of these pollutants is of primary importance.

SUMMARY, RECOMMENDATIONS, AND CONCLUSIONS

In this article we have demonstrated that use of equivalence principles can allow flexibility in providing ventilation for acceptable IAQ. This flexibility can allow a system to be used in a manner that reduces energy use, improves IAQ, reduces costs, improves comfort, or avoids the effects of occasional high outdoor contaminant levels, as appropriate to the situation.

The equivalent ventilation approach can shift loads to save energy or peak power, minimize ventilation during periods when ventilation could increase the intake of outdoor air with unacceptable contaminant levels, or to make best use of exogenous ventilation such as that provided by economizers or intermittent local exhaust. This approach is applicable to the ventilation rate procedures in ventilation standards.

The equivalent IAQ approach can be used to reduce ventilation rates when there are reduced contaminant sources or when source reduction is achieved by other means, such as air cleaning or filtration. This approach also forms the basis of an IAQ approach to ventilation and acceptable air quality standards and can be adapted as new COCs are identified or increased DALY values are derived from future toxicology and epidemiological studies.

The equivalent ventilation approach can be used over time frames ranging from a few hours to a year, but, for time periods much longer than a day, certain precautions should be taken. For example, the air change rate should not be allowed to drop to below about

20% of its target value for extended periods of time. This minimum could be supplied mechanically or by adventitious ventilation such as infiltration.

Both the ventilation and IAQ equivalence approaches facilitate the use of control technologies to allow ventilation systems to respond to real-time ventilation needs. An equivalent ventilation controller needs to sense the current ventilation, which can be reasonably done by sensing the status of ventilation-related equipment. A real-time IAQ controller is possible but currently less practical because appropriate contaminant sensors are lacking.

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Appendix A

Derivation of rule of thumb on fan sizing for recovering from under - ventilation periods

We wish to find a rule of thumb to determine how to size ventilation equipment when using a real-time controller to determine the ventilation system's operation.

We presume there will be periods when building occupants wish to turn off the ventilation system; during this period of time, indoor air contaminant levels will increase. Subsequently, there will be a period of time when the ventilation equipment will run to restore the total dose back to the desired level. To accommodate this "extra" operation, the ventilation system capacity must be increased beyond what is necessary for a system that would operate continuously.

To accomplish this, we must consider that we want the dose to even out and that we will only allow a maximum peak exposure and a maximum recovery time.

Assume that we start from an equilibrium position in normal operation and then we shut off the ventilation system. To be conservative, we will assume there is no incidental ventilation. During this period the relative exposure grows linearly with time as follows:

$$R(t) = 1 + A_{eq}t$$

until a peak is reached at

$$t_{off} = \frac{R_{max} - 1}{A_{eq}}$$

The relative dose during that period

$$= \frac{(R_{max}^2 - 1)}{2A_{eq}}$$

Now we turn on the ventilation system, and the relative exposure will decay:

$$R(t) = R_{max} e^{-A_{vent}t} + \frac{A_{eq}}{A}(1 - e^{-A_{vent}t})$$

The relative dose over time T which is presumed long is then

$$\frac{R_{max}}{A} + \frac{A_{eq}}{A}T - \frac{A_{eq}}{A^2}$$

Comparing the total dose to what the steady-state relative dose should be:

$$T + \frac{R_{max} - 1}{A_{eq}} = \frac{R_{max}^2 - 1}{2A_{eq}} + \frac{R_{max}}{A} + \frac{A_{eq}}{A}T - \frac{A_{eq}}{A^2}$$

From which we obtain:

$$\frac{(R_{max} - 1)^2}{2} = \frac{A_{eq}}{A}(R - \frac{A_{eq}}{A}) + A_{eq}T(1 - \frac{A_{eq}}{A})$$

Because we are looking at long times we use only the last term to get:

$$\frac{A_{eq}}{A} = 1 - \frac{(R - 1)^2}{2A_{eq}T}$$

Using a typical residential value of 1/3 ACH for the ventilation and assuming a 1-day recovery time, our rule-of-thumb for sizing the ventilation system becomes:

$$\frac{A_{eq}}{A} < 1 - \frac{(R_{max} - 1)^2}{16}$$

Note that the choice of 16 assures that peak relative exposures above 5 will be unacceptable.

This sizing allows for recovery from a single event in a reasonable length of time. If there is to be a regularly scheduled event, the intermittent ventilation equations of Sherman, Mortensen and Walker (2011b) could be used to determine sizing; the more stringent of the two should be used.