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Effect of Ventilation Strategies on Residential Ozone Levels

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Abstract

Elevated outdoor ozone levels are associated with adverse health effects. Because people spend the vast majority of their time indoors, reduction in indoor levels of ozone of outdoor origin would lower population exposures and might also lead to a reduction in ozone-associated adverse health effects. In most buildings, indoor ozone levels are diminished with respect to outdoor levels to an extent that depends on surface reactions and on the degree to which ozone penetrates the building envelope. Ozone enters buildings from outdoors together with the airflows that are driven by natural and mechanical means, including deliberate ventilation used to reduce concentrations of indoor-generated pollutants. When assessing the effect of deliberate ventilation on occupant health one should consider not only the positive effects on removing pollutants of indoor origin but also the possibility that enhanced ventilation might increase indoor levels of pollutants originating outdoors. This study considers how changes in residential ventilation that are designed to comply with ASHRAE Standard 62.2 might influence indoor levels of ozone. Simulation results show that the building envelope can contribute significantly to filtration of ozone. Consequently, the use of exhaust ventilation systems is predicted to produce lower indoor ozone concentrations than would occur with balanced ventilation systems operating at the same air-exchange rate. We also investigated a strategy for reducing exposure to ozone that would deliberately reduce ventilation rates during times of high outdoor ozone concentration while still meeting daily average ventilation requirements.

Keywords: Ozone; mechanical ventilation; filtration; ASHRAE Standard 62.2; infiltration; simulation

1. Introduction

Ozone is an air pollutant that can have significant health effects. The most important source of ozone is outdoor air and most ozone inside homes comes from outdoor air entering the homes. Studies examining the relationship between ventilation rates and health find improved health with increased ventilation rates because most pollutant sources are indoors [1]. The effect of ventilation on ozone is reversed compared to internally generated pollutants because it is a pollutant from outside the homes. Because people spend the vast majority of their time indoors, reduction in indoor ozone levels could lead to improved public health in terms of ozone exposure. A summary by Weschler [2] showed that indoor ozone inhalation accounts for 25-60% of total ozone inhalation and inhalation of ozone reaction products are much greater indoors than outdoors. Weschler's summary also showed that the connections between ill health and the products of ozone reactions indicated that it would be better to prevent ozone entering home to reduce concentrations rather than relying on reactions within the home and that concentrations on the order of 10 ppb can lead to significant health effects. Some recent work has been done [3,4] on finding interior building materials that remove ozone from indoor air without producing harmful reaction products. This work also showed that the materials present in the building envelope are less likely to produce harmful ozone reaction products than interior surfaces because they are not coated with fatty acids associated with cooking and human skin lipids that react with ozone to produce volatile organic compounds.

The ozone entering homes from outdoors along with ventilation air is due to the natural forces of wind and indoor-outdoor temperature difference that induce infiltration and natural ventilation, operation of natural draft appliances and fans that are used to induce ventilation airflows mechanically. As air flows through a building envelope the ozone it contains can react with the surfaces over which it flows. Therefore, the quantity of outdoor ozone reaching the inside space may vary depending on the properties of the specific paths the air flow takes through the building envelope. Laboratory studies have indicated that ozone filtration by building envelopes can occur depending on ozone reactions with indoor materials [5]. Walker et al. [6] provide a bibliography of ozone reactions with indoor materials and the magnitude of this reduction is highly variable and ranges from zero to 90% and depends on the specific building materials that the air flows over and the geometry of the air flow paths through the envelope. This is linked to the effect that different mechanical ventilation systems have on the air flow paths for entry of air into a building. For example, compare a continuous supply ventilation system to a continuous exhaust ventilation system. For the supply system, the outdoor air does not pass through the envelope – instead air enters the building via a fan and its associated ducting. In this case, filtration may occur at dedicated outdoor air filters, or by deposition on the ducting used to deliver the air. For the exhaust system, air enters through leaks in the building envelope and leaves via a fan and its ductwork. In this case, any filtration of air entering the building occurs in the flow paths in the building envelope.

Another mechanical ventilation system characteristic is the ability to change the ventilation rate with time. In particular, the ventilation rate could be reduced during times of high outdoor ozone concentration and then increased at other times in order to meet the minimum requirements. The effect of lowering ventilation rates at peak outdoor ozone times was examined in this study by turning off ventilation systems at peak times. The intermittent ventilation requirements of ASHRAE Standard 62.2 were met by ventilating more during off –peak times.

This study quantifies, through modeling estimates, the impact on indoor ozone concentration of alternative residential ventilation strategies. Residential ventilation includes exhaust fans, supply fans and balanced systems. For exhaust fans, air entering the building passes through the building envelope and ozone is removed by reaction with building materials that line cracks and other points of entry. The supply and balanced systems do not have air entering the home via the building envelope flow path and so do not have the ability to remove ozone before it enters the homes. This study focuses on residential buildings and the particular envelope air flow paths and ventilation systems used in residences in the United States. The modeling has two parts. The first calculates the mass flow rates through individual building envelope air leakage sites and mechanical ventilation systems including the effects of wind and indoor-outdoor temperature differences. The second part calculates a mass balance for ozone that includes internal deposition and deposition in leaks that varies from leak to leak depending on the material properties and leak geometry. The outdoor ozone profiles were taken from California Air Resources Board (CARB) data [7]. The days with the highest ozone levels were selected as these will allow easier observation of differences between the ventilation systems. The particular days chosen were the peak ozone days for 2007: for Riverside this was August 12th and for Livermore this was July 22nd. Figure 1 illustrates the hour-by-hour outdoor ozone profile for these two days and locations – these concentrations are much higher than to 10 ppb discussed earlier that is considered to be high enough for health impacts to be an issue. The weather data used in the air flow calculations was taken from local weather stations for the same day as the outdoor ozone profile.

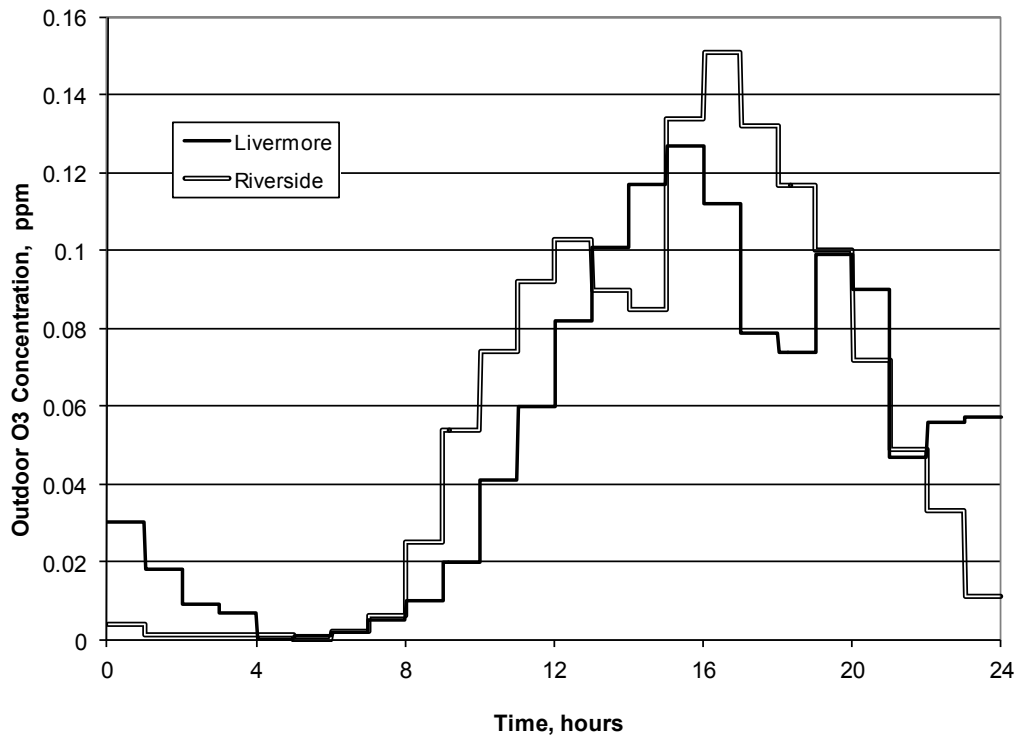


Figure 1. Outdoor ozone profiles for the peak ozone days in Livermore, CA and Riverside, CA.

There are four key ventilation/filtration parameters that determine the effect of the different ventilation options:

1. *Quantity of air flow.* Generally, less air flow means less ozone transported into the building. This must be balanced with the requirements of ASHRAE Standard 62.2 [8] that provides minimum whole house ventilation requirements for acceptable indoor air quality by diluting indoor pollutants with outdoor air. The mechanical ventilation systems in this study were sized to meet the ASHRAE 62.2 minimum requirements. In the case of intermittent ventilation the ASHRAE 62.2 intermittent ventilation calculation procedures were used to determine the air flows when the fans were operating. Similarly, the number of hours of credit during which mechanical ventilation is not needed due to economizer operation were also determined using the ASHRAE 62.2. Procedures. The air flow rates in this study were calculated using a ventilation, heat transfer and Heating, Ventilating and Air Conditioning (HVAC) equipment simulation tool called REGCAP that has been used in several previous studies of envelope air flows and their interactions with HVAC systems [9, 10, 11]. REGCAP was particularly suited to use in this study because it separates the air flow in and out of the house into specific leakage sites to which we can assign the different ozone penetration factors and thus evaluate the effect of using different air flow paths for outdoor ozone entry depending on the ventilation system used. The REGCAP tool combines a ventilation model, a heat transfer model and a simple moisture model. The ventilation model is a two-zone model: the attic and the house below it, and they interact through the ceiling flow. Both zones use the same type of flow equations and solution method. The total building and attic leakage is separated into components (such as 4 walls, ceiling, floor, flue, etc.). The flow for each component is determined by a power-law pressure - flow relationship with a flow coefficient, C , that determines the magnitude of the flow and an exponent for pressure difference, n , that determines how the flow through the leak varies with pressure difference. The ducts are modelled differently depending on if the air handler is on or off. When the air handler is off, the duct leaks are assumed to experience the same pressure difference as the ceiling. Air then flows between the house and the attic via these leaks. When the air handler is on, supply leaks enter the attic and return leak flows are from the attic to the return duct and there are register flows between the ducts and the house. The ventilation rate of the house and the attic is found by determining the internal pressures for the house and attic that balances the mass flows in and out. The heat transfer model determines the temperature of the house and attic air and other building components (e.g., pitched roof surfaces and ducts). A lumped heat capacity method is used to divide the attic, house and HVAC system into several nodes, and an energy balance including conduction, convection and radiation heat transfer is performed at each node to determine the temperatures. The simulation uses minute-by-minute time steps to account for cycling of HVAC equipment.
2. *Time of operation.* ASHRAE Standard 62.2 allows ventilation rates to change with time so long as various criteria are met. This allows for the possibility of reduced ventilation rates at times of high outdoor ozone concentrations, with increased ventilation at other times. Since ozone exhibits a strong diurnal profile, this strategy may offer a practical means to improve indoor air quality. Because the high ozone concentrations are coincident with high outdoor temperatures there is also the potential for reduced energy use.
3. *Air flow path.* This includes details of the air flow geometry for air flowing through the building envelope (including cracks, ducts, supply air filters, etc.) and relating envelope construction details to air flow path geometry and deposition. This changes the potential for deposition in the various air flow paths.

4. *Flow path materials.* Laboratory testing has shown that different materials react with ozone at different rates and generate different reaction products. The different reaction rates lead to changes in filtration potential. This study evaluated the effect of different mechanical ventilation systems on the air flow path and associated envelope materials.

A couple of factors will not be addressed in this paper because the mechanisms are poorly understood and the effects are not well quantified. The first is byproducts of ozone-initiated chemistry and the second factor is the time dependence of surface reactivity: aging and recovery. A more detailed discussion of these issues can be found in Walker et al. [6].

2. Calculations of indoor ozone concentration

The indoor ozone estimates were based on a single zone mass balance model that depends on air flows in and out of the building, the incidental filtration provided by individual air flow paths, deliberate filtration by the HVAC system, and deposition on interior surfaces. A single zone model was used because there are insufficient data available to describe the air flow and ozone characteristics of zone-to-zone interior flows making a multi-zone approach impractical. In addition, the comprehensive validation data required for a multi-zone model are not available. The following differential equation was used to describe the rate of change of indoor ozone concentration with time:

$$\frac{dC_{O_3,in}}{dt} = \left[\sum_i P_{O_3,i} Q_{in,i} C_{O_3,out} \right] - [Q_{out} + k + \eta Q_h] C_{O_3,in} \quad (1)$$

Here, $C_{O_3,in}$ is the indoor ozone concentration, $C_{O_3,out}$ is the outdoor ozone concentration, $P_{O_3,i}$ is the penetration factor of ozone for leak path i (including filtration for supply air), $Q_{in,i}$ is the volume-normalized air flow rate into the house (in air-changes per hour, h^{-1}) through flow path i , Q_{out} is the volume-normalized air flow rate out of the house (h^{-1}), Q_h is the volume-normalized air flow rate through the HVAC system (h^{-1}), k is the indoor deposition loss-rate coefficient (h^{-1}), and η is the single-pass ozone removal efficiency in the HVAC system. Based on data in Hyttinen et al. [20], we set the value of η to be 5%, whenever the HVAC system is on. The air flows were assumed to be quasi-steady over the short time period of one minute for the simulation steps. Equation (2) was used as a discrete approximation of equation (1) for evaluating the time-varying level of indoor ozone, with $\Delta t = 1 \text{ min} = 0.0167 \text{ h}$:

$$C_{O_3,in}(t) = C_{O_3,in}(t - \Delta t) + \Delta t \times \left(\left[\sum_i P_{O_3,i} Q_{in,i}(t) C_{O_3,out}(t) \right] - [Q_{out}(t) + k + \eta Q_h] C_{O_3,in}(t - \Delta t) \right) \quad (2)$$

In many field studies results are expressed as indoor:outdoor concentration ratios. These field data will be used as a validation of the modeling/simulation approach, therefore the concentrations calculated using the above technique were also expressed as a fraction of the coincident outdoor concentration. In rough terms, not accounting for envelope deposition or HVAC system removal, the indoor:outdoor ratio of the time averaged concentrations is given by Equation 3, where Q is the air-exchange rate for the house and k is the deposition factor.

$$\frac{C_{O_3,in}(t)}{C_{O_3,out}(t)} = \frac{Q}{Q + k} \quad (3)$$

3. Ozone removal by the building envelope

The extent of ozone penetration through building envelopes depends on air flow velocity, crack geometry, and reaction probabilities on the surface. The relationships describing ozone deposition calculations for the building envelope were based on previously published work [5, 21]. In this study we focused on applying these models to common air leakage paths for homes in a way that enables us to estimate indoor concentrations. Different performance parameters related to ozone removal were assigned to the different leakage paths in the building envelope depending on their geometry and construction materials.

The removal of ozone by the building envelope was separated into two main categories corresponding to different air flow paths: flow through cracks and flow through insulation. The floor level leakage was assumed to flow through cracks, and the wall and ceiling flows are through insulation. We further separated the air flow entering the building through cracks into flow through cracks in the walls and ceiling, and flow through floor levels leaks where one surface is the concrete foundation slab.

The mean velocity, $\bar{V}$, of air flow in a crack is given by Equation 4:

$$\bar{V} = \frac{Q}{A} \quad (4)$$

where Q is the volumetric air flow rate and A is the cross-sectional area of the flow path.

The relationships used to determine ozone penetration in cracks were taken from the analysis given in [5]. The penetration factor (P_{O_3}) for ozone in cracks was given by:

$$P_{O_3} = \exp\left(-\frac{2V_o L}{\bar{V}d}\right) \quad (5)$$

where V_o is the deposition velocity and d is the crack height (m).

To calculate ozone deposition in cracks we used the relationships developed in [5]. We used the following values for ozone-surface reaction probability — For glass fibers: $\gamma = 6 \times 10^{-6}$ for freshly exposed glass fibers [5] - with a surface uptake deposition velocity of 5.4×10^{-4} m/s; For concrete: $\gamma = 4.4 \times 10^{-5}$ to 10^{-4} for outdoor surfaces and 7.9×10^{-5} for a slab [28]. Given this range a central value of 5×10^{-5} was selected for concrete-faced cracks. For plywood (using the same value for wood surfaces): $\gamma = 4.7 \times 10^{-6}$ to 5.8×10^{-7} [18]. A central value of 1×10^{-6} was used in the calculations.

More recent work has included more thorough measurements for wood and concrete and gives values of surface uptake deposition velocities directly:

- 0.00080 m/s for coarse concrete and 0.00017 m/s for fine concrete at 50% RH [29].
- 0.00022 m/s for untreated unfinished wood at 50% RH [29].
- Deposition velocity for gypsum wallboard is 0.0012 m/s [30].

Grøntoft [31] found a reduction in deposition velocity for successive tests of an individual sample. This implies that the deposition rate will vary depending on the deposition history of the surface. The decrease was about 20% for concrete floor tile. Given the paucity of data on the reduction in deposition velocity, particularly for the materials of interest in this study, this effect was ignored. In addition, there are sure to be variations in deposition velocity with temperature, and, again because of the lack of

necessary data, these effects were ignored. The values used in the current study are those at steady state.

For all but the largest concrete faced cracks, the air flows and crack geometries of interest in this study result in deposition velocities that are limited by the surface-uptake deposition velocity that is typically an order of magnitude lower than the mass transport velocity. For example, a wood faced crack at 0.1 m/s has a surface uptake velocity of 0.00023 m/s and a mass transport velocity of 0.007 m/s.

For a flow path through a wood-faced envelope crack, the ozone penetration for three different crack heights is shown in Figure 2. The results in Figure 2 show that for the larger leak characteristic of 10 mm the penetration factor is greater than 95% under typical conditions (air velocity > 0.1 m/s). For concrete, the higher reaction probability results in less ozone penetration, as shown in Figure 3.

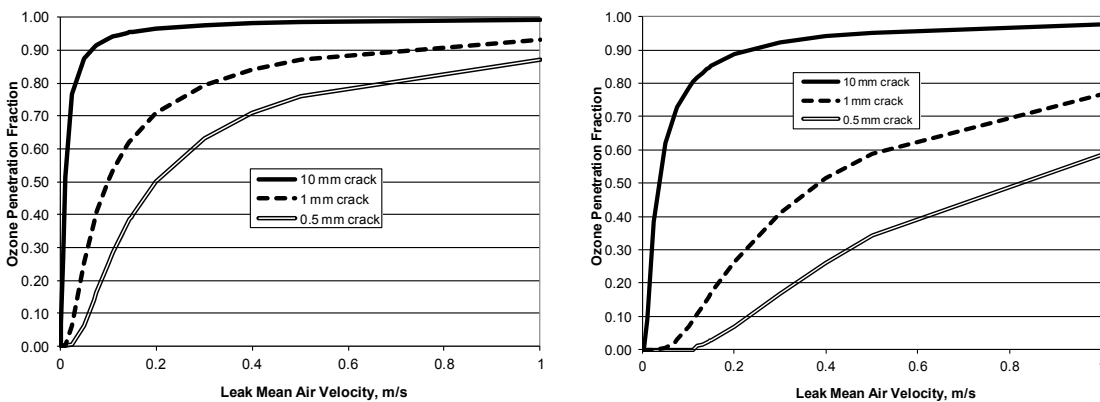


Figure 2. Ozone penetration in 0.15 m long wood faced (left) and concrete faced (right) cracks.

The results for 0.15 m long paths are appropriate for air flow paths that do not flow through the cavity insulation. For flow through the wall cavity and the ceiling, the air flow path also includes about 1 cm of gypsum wallboard on the interior surface and about 1 cm of exterior sheathing - commonly plywood. Figure 3 shows that the short crack has essentially total penetration at velocities greater than 0.1 m/s, indicating that the deposition in plywood and gypsum board sheathing can be neglected and the deposition inside wall cavities and ceiling insulation dominates for these flow paths.

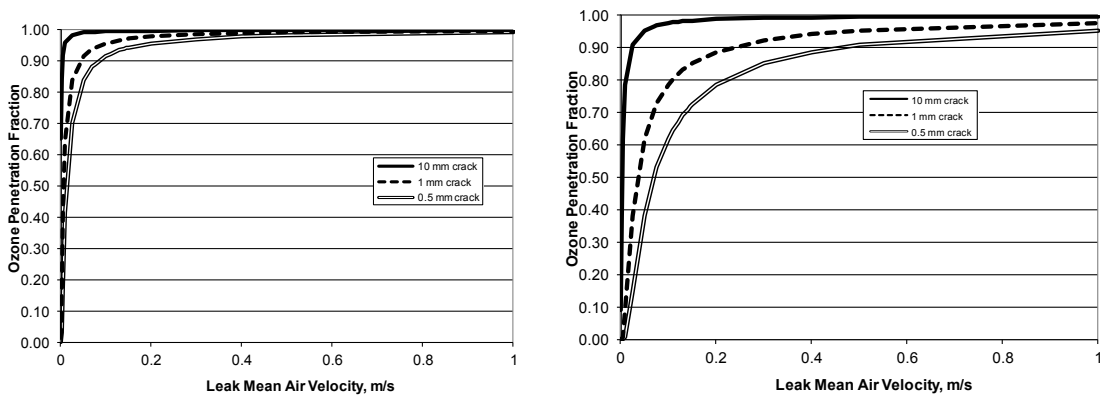


Figure 3. Ozone penetration for a short 0.01 m long wood faced (left) and gypsum faced (right) crack.

The crack at floor level will have one face that is wood and the other that is concrete. Thus, the two faces of the crack have different uptake coefficients. A previous analysis [5] reported the basic work on this topic, but limited their analysis to cases in which the crack walls had common reaction rate coefficients. The following analysis determines the relationships for a crack with two different faces. The flow through the crack is represented in two dimensions, with the top and bottom surfaces lining the flow channel. A steady-state material balance equation is written on ozone over an along-stream segment of thickness Δx . If the rate of deposition uptake is the same on both surfaces, then the material balance would be written as follows:

$$\bar{V}dWC\left(x - \frac{\Delta x}{2}\right) = \bar{V}dWC\left(x + \frac{\Delta x}{2}\right) + 2V_o\Delta xWC(x) \quad (6)$$

In equation (6), the first term on the left represents advective transport into the control volume. The terms on the right represent, respectively, advective transport out of the control volume and depositional loss on the top and bottom surfaces. The “deposition velocity” model was used for surface loss, where the flux to a surface is equal to $V_o C$, with V_o being the deposition velocity.

To combine the effects of mass transport and surface reaction, we follow the previous approach of Liu and Nazaroff [5] and create a linear model of the deposition process in which the mass transport and surface reaction process act in series. The overall flux to either surface is $2V_oC$, and series process treatment produces this relationship:

$$V_o = \frac{V_s V_t}{V_s + V_t} = \left(\frac{1}{V_s} + \frac{1}{V_t} \right)^{-1} \quad (7)$$

Where V_s is the surface reaction velocity and V_t is the mass transport velocity. Allowing for different surface reaction rates for two different crack surfaces (e.g., wood and concrete) that correspond to V_{s1} and V_{s2} , we can write the combined expression for the dependence of the overall deposition velocity on the surface uptake limited deposition velocities and the transport-limited deposition velocity.

$$V_o = \frac{V_t(V_{s1}V_t + 2V_{s1}V_{s2} + V_{s2}V_t)}{2(V_{s1} + V_t)(V_{s2} + V_t)} \quad (8)$$

The surface uptake-limited deposition velocities are estimated knowing the total deposition velocities (0.00022 m/s for wood and 0.00080 m/s for concrete) given by Grøntoft and Raychaudhuri [29] at particular transport deposition velocities. For wood, $V_s = 0.00022$ m/s (the same as V_o) and for concrete, $V_s = 0.0009$ m/s. These values of V_s were used together with V_t calculated for each time step in the simulations in order to obtain V_o for each time step, and thereby determine ozone penetration using Equation 5. Figure 4 shows the resulting ozone penetration for a two faced crack, with one face of wood and the other of concrete.

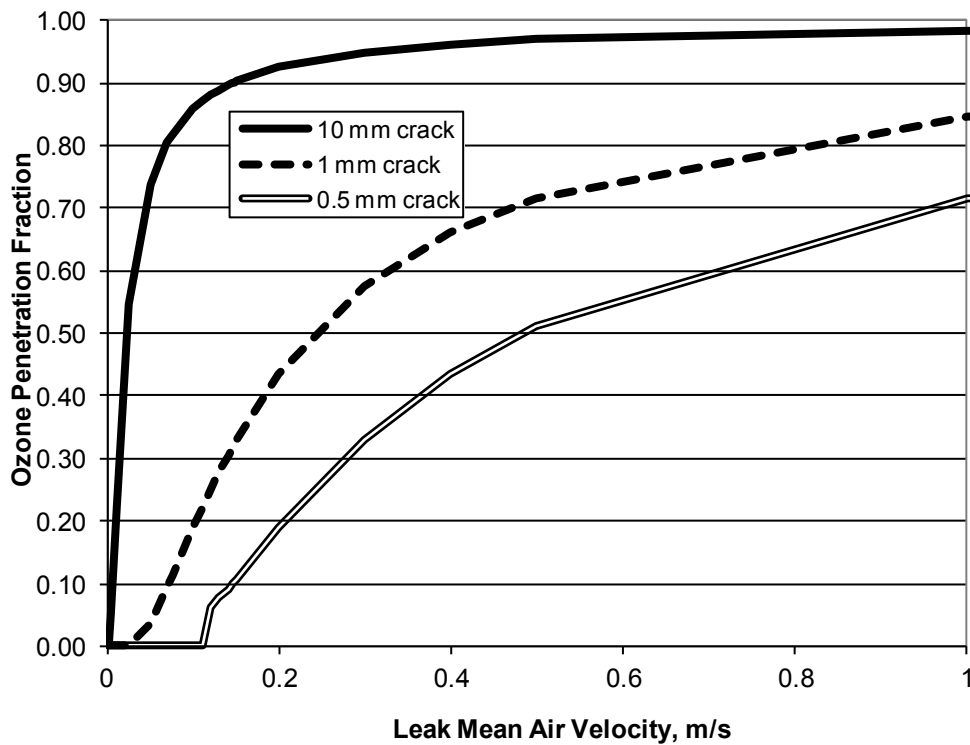


Figure 4. Ozone penetration for a 2 faced crack - one face is wood, the other concrete.

The wall and ceiling leaks both have air flows through glass fiber insulation in addition to having leaks through or around the solid components. For the walls, the insulation is in a cavity where the inner cavity face is gypsum wallboard and the exterior face is plywood sheathing. The ozone filtration in insulation is different from that through cracks and depends on the glass fiber diameter, fiber packing density (solidity), mean air velocity and flow path [5]. For glass fiber insulation, the fiber diameter is well known and is assumed to be the same for all the insulated cavity air flow paths. The ozone removal is then determined by the geometry of air flow through the insulation. The fraction of total air flow through insulation for wall and ceiling leaks is given by the parameter “ f ”.

For wall cavities, there are two extremes of cavity flow. One is flow that is straight through the wall (horizontal flow) and has a path length of the wall thickness. The second is vertical flow through the cavity, where the path length is the full cavity height. In our calculations, we assumed typical wall dimensions with a wall thickness of 0.15 m and a cavity height of 2.5 m. The vertical flow in wall cavities has a much greater path length and will have almost total ozone removal; however, this flow path has a high air flow resistance and only a small fraction of the total envelope air flow will take this path (in our example the path length is 17 times greater than for the horizontal flow and therefore a factor of 17 less air flow), that reduces the potential for ozone removal. In other words, this vertical flow path will have a lot of ozone removal from only a small fraction of the air entering the building, resulting in little change in overall envelope ozone removal efficiency. Therefore, the calculations in this study only include the horizontal flow. This yields penetration factors similar to the range of 0.62 to 1.0 (with a mean of 0.79) found in a field study estimation of penetration factors [19].

The ozone penetration through a wall section with fiberglass insulation is given by:

$$P_{O_3} = f \times \exp\left(-\frac{4W_o\alpha L}{Vd_f}\right) \quad (9)$$

where: α is the solidity of the insulation (about 0.003 for glass fiber) and d_f is the fiber diameter (about 10×10^{-6} m or 10 μ m). L is the flow path length that changes for wall and ceiling air flow paths. Figure 5 shows the ozone penetration fraction for the three different glass fiber filled air flow paths with $f = 1$ (i.e., all flow goes through the insulation).

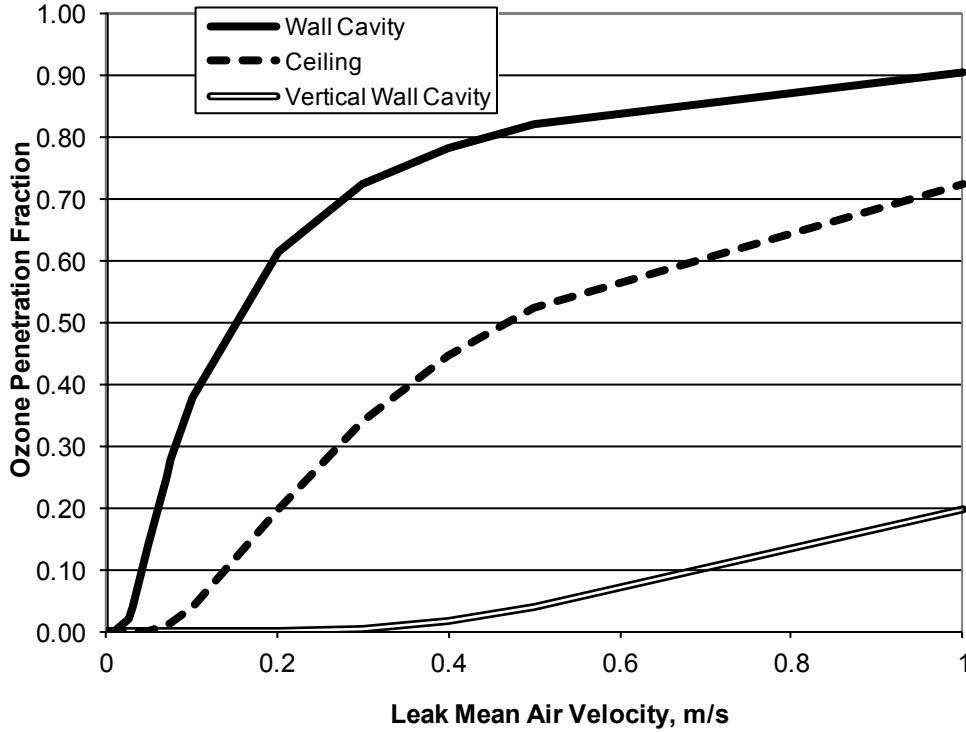


Figure 5. Ozone penetration factors through glass fiber insulation for a 0.15 m wall cavity, a 0.5m thick ceiling insulation blanket, and a 2.5 m tall vertical wall cavity flow path.

To determine the ozone penetration, the air velocity through the insulation is required. We determined the mean air velocity for air flowing through the insulation using the geometry of the air flow, where the mean air velocity is given by Equation 2 using the volumetric air flow rate (from the air flow model) and the cross-sectional area of the flow path. The mean velocity was determined for three different air flow paths:

1. The 0.15 m straight through wall gives a mean velocity of 0.0009 m/s,
2. the 0.5 m of ceiling insulation has a mean velocity of 0.00027 m/s, and
3. the 2.5 m vertical flow path through a wall cavity has a mean velocity of 0.0005 m/s.

At these low velocities, there is almost zero penetration of ozone.

Before assuming that we could assume zero penetration of ozone, we recalculated the velocities at a higher leak pressure of 5 Pa, in which case the air flows increase to 0.0046 m/s, 0.00138 m/s and

0.00028 m/s for the same three air flow paths. These air velocities are still not high enough for there to be any ozone penetration. These calculations imply that penetration can be assumed to be zero all the time for air flow through the glass fiber insulation in the ceiling, so ceiling air flows will not transport any ozone into the building. Therefore the critical parameter determining deposition rates for ceiling air flows is f . Reasonable values for indoor concentrations compared to measured field data can be obtained by assuming half of the inflowing ceiling air flows bypass the insulation, i.e., $f = 0.5$ [6]. With no bypass the resulting indoor concentrations are too low compared to the measured field data.

The floor level leaks have two faces: the wood of the framing and the concrete of the slab/foundation. Each face has its own ozone reaction properties, and the expression for deposition velocity (V_o) for a two-faced crack given by Equation 8 was used, with fixed values of $V_s = 0.00022$ m/s for wood and 0.0009 m/s for concrete. V_o was used in Equation 9, together with crack geometry (10 mm height and 0.15 m length) and air velocity to estimate the ozone penetration. Each of the four floor level leaks has its own air flow, air velocity and ozone penetration factor because the air flow through each of the four floor level leaks is different – and may not even be in the same direction. The relationship between air flow velocity, crack dimensions and the leak pressure exponent is based on the methods developed by Sherman [27]. Assuming a typical leak pressure of 2 Pa and a crack length of 0.15 m the crack area is 0.000082 m² corresponding to a crack diameter of 10 mm and the mean air speed is 0.6 m/s.

4. Field measurements of ozone in homes

The results of field measurements from other studies were used for two purposes in this study. The first was to determine typical ratios of indoor to outdoor ozone concentrations as a check on the simulation predictions. The second was to determine input values for parameters used in the simulations. The ratio of indoor to outdoor ozone concentrations has been measured in several studies: An extensive summary of indoor-outdoor ozone concentration ratios measured in about 60 studies covering a wide range of buildings was reported in Weschler [2]; indoor to outdoor concentrations of 0.37 ± 0.25 for 136 were found in southern California homes [12]; and indoor to outdoor ratios of 0.20 ± 0.18 in 145 Mexico City homes [13]. A complication in interpreting the indoor to outdoor ozone concentration ratio in these studies was that many of the homes had open windows during sampling. Homes with open windows will have no ozone removal as air flows through the window opening and thus result in higher indoor concentrations compared to homes with closed windows. Data from the National Morbidity, Mortality, and Air Pollution Study have been correlated with US Census and American Housing Survey data, and showed reduced mortality due to ozone exposure and the presence of central air conditioning in homes (which are likely to be homes with less window opening) [14], with the caveat that the presence of central air conditioning is highly correlated with higher temperatures, i.e., when window opening is less likely to be used for comfort. Focusing on homes with closed windows several studies report that the resulting indoor-outdoor concentration ratio is about 0.1 [15, 16, 17]. These measured values will be used as a check on the simulations. Given the large ranges found in these studies, a target range of indoor to outdoor ozone concentration ratios is about 0.05 to 0.4. So long as the ratios are within this reasonable range, this study will then concentrate on the relative changes in indoor concentration depending on the ventilation technique employed.

In addition to indoor:outdoor ratios, some studies have determined the deposition factor, k , in Equation 3 and are summarized by Weschler [2]. The most relevant for houses were for 43 homes with a mean deposition factor over all the houses of 2.8 per hour – with significant variation from house to house leading to a standard deviation of 1.3 per hour [15]. So, the 0.05 to 0.4 range of indoor to outdoor

ozone concentration ratios corresponds to air-exchange rates in the range 0.15 to 2 per hour if envelope deposition is ignored. Other field studies [2, 18] showed values of interior deposition that changed significantly with HVAC system operation: the interior deposition coefficient changing from 2.9 (similar to the 2.8 from [15]) for no HVAC operation to 5.4 with HVAC operation. To account for this effect in our simulations we will include the effects of increased ventilation rates due to HVAC system air leakage and ozone deposition on HVAC system filters.

Overall, these field measurements suggest that interior deposition is a significant contributor to reductions of indoor ozone concentration. This has the effect of lowering the mean values of indoor ozone concentrations. So, although this study focuses on the differences in indoor concentration due to the operation of different mechanical ventilation systems, primarily due to envelope deposition, it is important to realize that interior deposition has a significant effect on the indoor ozone concentration. A recent study [19] measured ozone penetration in eight houses by measuring the decay of artificially elevated ozone levels simultaneously with fan induced ventilation. The results showed a mean ozone penetration rate of 0.79 (ranging from 0.62 to 1.0) indicating that ozone removal as air travels through the envelope is significant. Combined with a measured indoor deposition rate of 9 per hour (much higher than other estimates primarily due to operating mixing fans during the experiment) the estimate of indoor:outdoor concentration was 0.05, which is in line with other estimates. The authors concluded that this ozone removal as air flows through the envelope is a “preferred first line of defense against indoor exposures to outdoor ozone and its byproducts”.

5. HVAC system filtration

To account for the filtration of ozone provided by HVAC system filters, it was assumed that the filters are dirty (as these are the most likely to be in place in residences.) Dirty filters remove 3 to 20% of the ozone [20]. A typical value of 5% of ozone removal was used for central forced air system filter and for the filters on the supply side of HRV and continuous supply systems.

6. House characteristics

Houses were simulated for two climate zones that had high outdoor ozone levels: Livermore, CA, and Riverside, CA. The house characteristics were based on a California State Energy Code [22] prototype home that is a slab-on-grade, two-story, with a floor area of 164 m². The wall surface area was estimated from measured data from several thousand new homes [32]: the wall area was typically 1.54 times the floor area for a two-story home. Window area was 20% of floor area with windows equally distributed on the four exterior walls.

The assumed total envelope leakage was chosen as a typical value for new home construction and is the default in California’s residential building energy code [22]: Specific Leakage Area of 4, corresponding to a flow coefficient (C) of 0.067 m³ s⁻¹ Pa⁻ⁿ. The envelope pressure exponent was assumed to be $n = 2/3$ and was assumed to be the same for all leaks and independent of flow rate based on a large national database [23]. The pressure exponent has been shown to be constant over the pressure and flow range of interest [24]. The wind pressures included local shielding by adjacent buildings based on the wind shadow shelter method of Walker et al. [25]. The houses were assumed to be in a typical urban environment with houses in a row on a street. The envelope leakage distribution was assumed to be 15% at floor level, 50% in the walls and 35% in the ceiling based on default values in the ASHRAE Handbook of Fundamentals [26]. The wall and floor level leakage was split into four equal parts – one

for each face of the building. The heating and cooling systems were modeled to include air leakage between the ducts and attic at 5% of total system flow (2.5% supply leaks and 2.5% return leaks).

7. Ventilation systems

In addition to the ventilation systems outlined below, the house had a bathroom exhaust that operated from 7:30 to 8:00 a.m. (two 25 L/s fans) and a kitchen exhaust that operated from 5:00 p.m. to 6:00 p.m. (an 80 L/s fan). The simulations evaluated the following ventilation systems that are all ASHRAE Standard 62.2 compliant (except for open windows) and commonly used in residences:

1. *Continuous exhaust.* This continuously depressurized the house, and the incoming air enters through the building envelope. Depending on envelope leakage and weather conditions, the flow path for air entering the home could change (e.g., between floor, ceiling or wall leaks), and with it the ozone removal.
2. *Intermittent exhaust.* In addition to the characteristics of the continuous exhaust, this system had the capability to be turned off at times of high outdoor ozone levels. This can be done by simple timers, in response to an alert, or, conceivably, through internet-based information linked to real-time local ozone reporting. In the simulations, a timer was used to turn off the exhaust system for four hours at a time. In summer, the off period was from 3:00 p.m. to 7:00 p.m. (coincident with the electrical system peak load and also avoiding some periods of high ambient ozone). In winter, the off period was from 1:00 a.m. to 5:00 a.m. The intermittent exhaust was sized to meet ASHRAE 62.2 and, therefore, had 20% more air flow than the continuous exhaust.
3. *Heat Recovery Ventilator (HRV).* The HRV had balanced air flow which meant that the envelope flows were generally unchanged during operation.
4. *Central Fan Integrated Supply (CFIS) with continuous exhaust.* This system utilized both supply and exhaust, with the supply operating for 20 minutes out of each hour in conjunction with the central furnace or air conditioning blower.
5. *Continuous supply.* This system continually pressurized the house and incoming air enters mostly through the fan and exits through the building envelope. Depending on envelope leakage and weather conditions, the exact flow path could change, and with it the ozone removal.
6. *Economizer.* An economizer was modeled as a supply fan with a flow set equal to the HVAC central system blower at cooling speed. The economizer operates when the indoor temperature is above 21 °C and the outdoor temperature is 3.3 °C or more below the indoor temperature setpoint. Although the economizer has very high airflows, the long off times mean that it is not possible to be ASHRAE 62.2 compliant with the economizer alone. Relationships have been developed between high and low ventilation rates and their respective operating times [33] that indicate that for the long (16 hours for Climate Zone (CZ) 10) off times there is no economizer air flow rate that would allow this system to meet ASHRAE 62.2 over a 24 hour period. However, it is possible to take credit for this over-ventilation. Credit can be taken for over-ventilation/economizer operation (i.e., time during which no mechanical ventilation is required) [9]. In this case of roughly 6 hours of economizer operation there is 10 hours of credit available. To minimize ozone entry, it makes sense to take this credit between the hours of 10:00 a.m. and 8:00 p.m. This means that that additional mechanical ventilation occurs when the economizer is off before 10:00 a.m. and after 8:00 p.m. During these times, the outdoor ozone concentrations are low and will not significantly contribute to the indoor ozone concentration.
7. *Open Windows.* In previous studies and summaries [12, 2], it has been shown that open windows significantly increase indoor ozone levels when outdoor ozone levels are high. This

outcome is understood to be due to a combination of significantly (at least by factors of two) increased ventilation rates and zero filtration of entering air.

In addition to the whole building ASHRAE 62.2 compliant ventilation systems, the house had a bathroom exhaust that operated from 7:30 to 8:00 a.m. (two 24 L/s fans) and a kitchen exhaust that operated from 5:00 p.m. to 6:00 p.m. (a 75 L/s fan).

8. Ventilation results

An example of the incoming ventilation air flow rates are shown in Figure 6 for the continuous fan, where a positive value for flow is flow into the house and a negative value is flow out of the house. The figure shows the flow through the ceiling and inflows only through wall and floor leaks (each of the four wall and floor leaks were summed to get the building total). These air flows are in kg/s. To convert to Air Changes per Hour (ACH), one must multiply by 6.8: e.g., the highest air flows in Figure 6 (when the kitchen exhaust is on) correspond to about 0.95 ACH. The effect of the morning/evening bathroom and afternoon kitchen exhaust stand out in these results. From 2:00 p.m. to 6:00 p.m. the duct leakage increases the ventilation rate by about 0.02 kg/s (0.14 ACH). The cooler indoor temperatures during the daytime result in inflows through the ceiling and outflows through the floor - resulting in no inflow through the floor. The continuous supply pressurizes the house resulting in less inflow for other envelope flow paths. In this case, the ceiling rarely has any inflow, as shown in Figure 7. The variability of flow magnitude and direction was used as input to the indoor ozone calculations. It was important to separate the leaks in this way and know which leaks were contributing to air flow into the building (and the magnitude of the flows in these leaks) so that the different ozone removal rates for each leak could be applied.

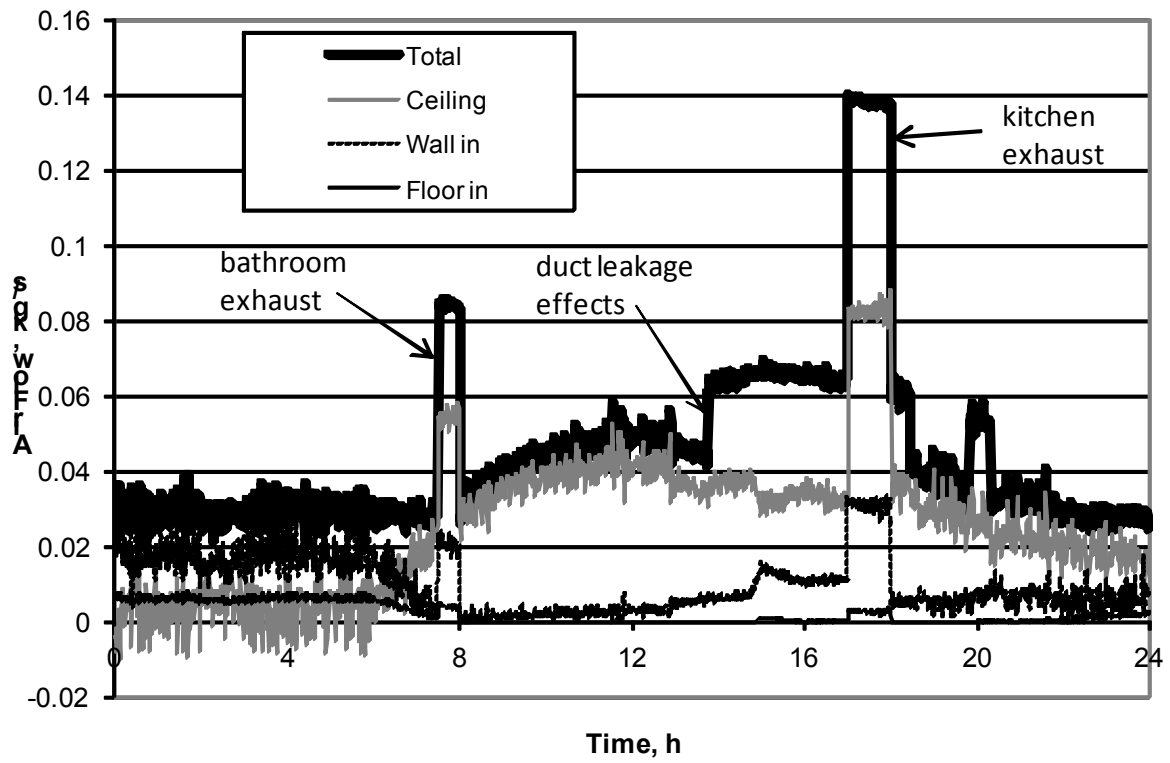


Figure 6. Envelope air flows for continuous exhaust in Riverside.

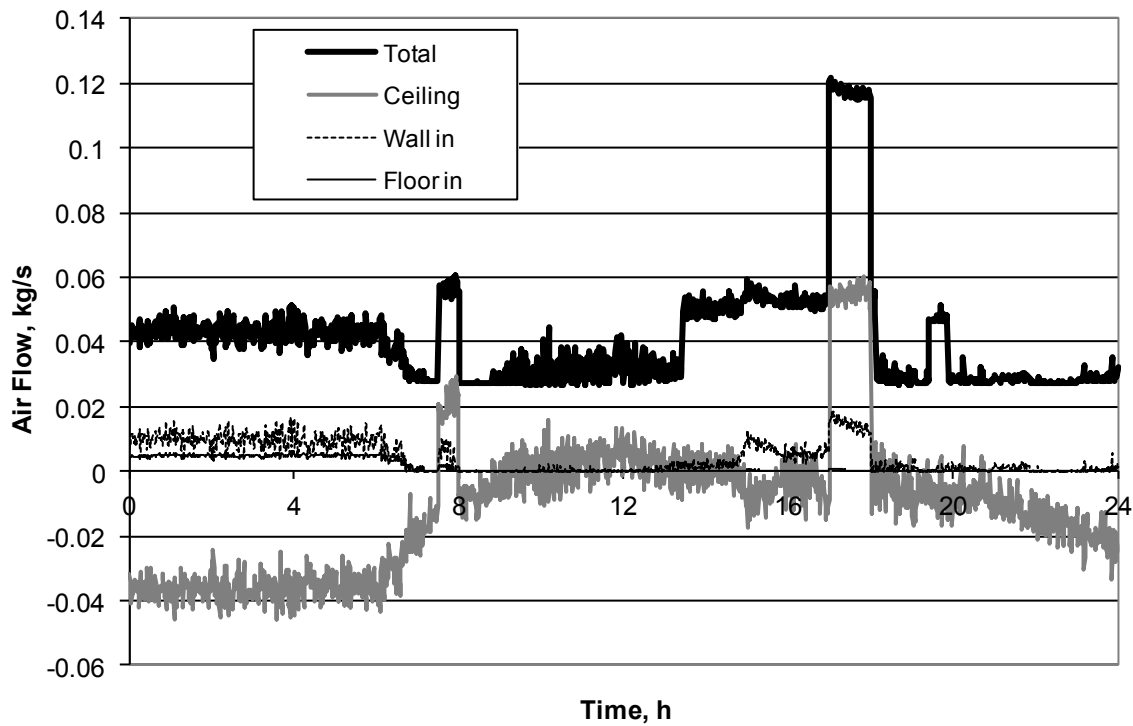


Figure 7. Envelope air flows for Continuous Supply in Riverside.

9. Results and Discussion

Some additional simulations were performed in order to provide context for the envelope filtration results by assuming no envelope filtration and looking at the effect of open windows for comparison to field data to further verify model predictions. With no envelope filtration the internal deposition combined with a small amount of filtration from the HVAC system filters brings down the indoor ozone concentrations by about 80%. Measured field data for houses with normally open windows had indoor:outdoor concentration ratios averaging 0.68 ± 0.18 [15]. To see if the simulations can replicate this result, a simulation was run for Riverside using open windows - one on the first floor and one on the second floor. Each window had a 1m high by 0.5 m wide opening. The results were that the ratio of average indoor:outdoor concentration is 0.47 (the average of the ratios is 0.40 and ratio of peaks is 0.58). The big increase in ventilation results, as expected, in large increases in interior ozone. Without knowing more about the weather or window opening details in the measured field data, the results are reasonable. Figure 8 shows these effects relative to each other for the case of continuous exhaust.

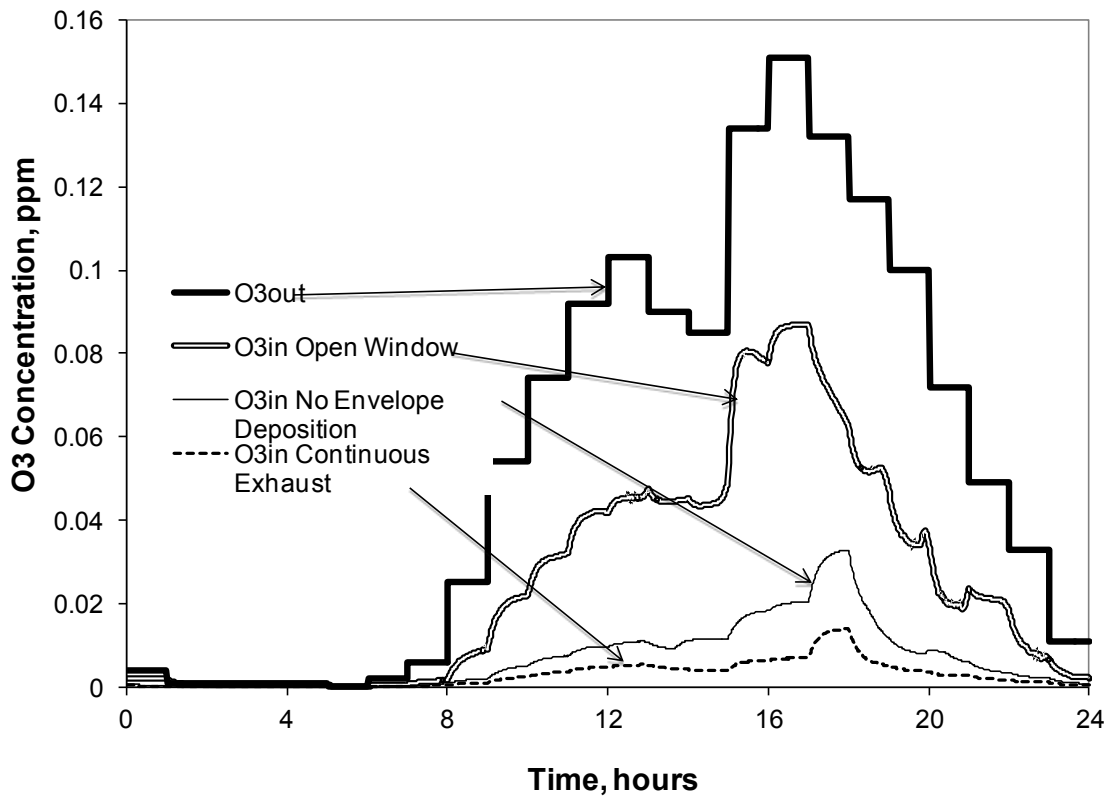


Figure 8. Effect of open window, no envelope deposition and inclusion of envelope filtration (for the case of continuous exhaust) for Livermore

Figure 9 compares the outdoor concentrations to indoors for the continuous exhaust in Riverside. As a check on the validity of the results, the concentrations shown in Figure 9 for Riverside with continuous exhaust can be compared with field measurements of Lee et al. [15]. Figure 9 shows that the indoor concentrations generally follow the outdoor ones – but at a much lower level. The case shown in Figure 9 is for continuous exhaust that maximizes ozone reductions due to interactions with the building envelope and represents the best case for envelope ozone removal resulting in an average indoor:outdoor concentration ratio of 0.053. This best case situation is at the low end of field data.

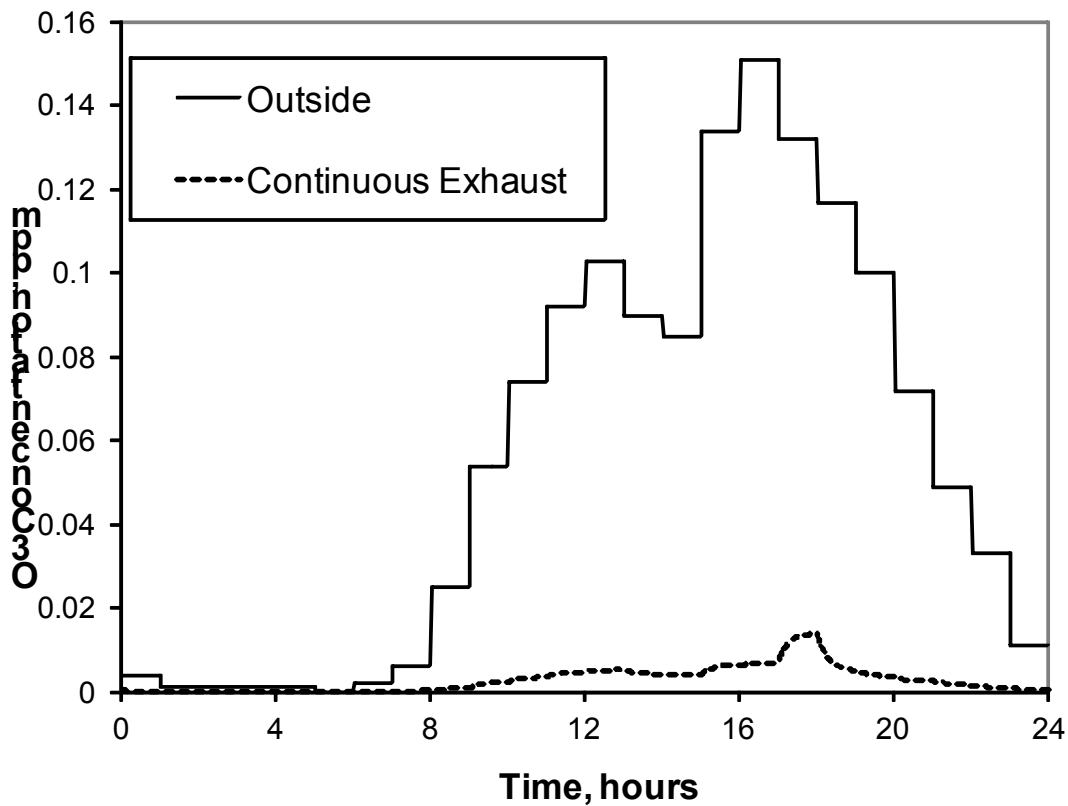


Figure 9. Indoor and outdoor ozone concentration in Riverside for continuous exhaust.

Figure 10 compares the indoor ozone concentrations for all the ventilation system alternatives in Riverside (the results for Livermore are essentially the same – just with a slightly different profile due to the different outdoor ozone profile). The spike upward in ozone concentration for all the systems at hour 17 is due to the operation of the kitchen exhaust fan, as seen in Figures 6 and 7. The economizer has the lowest concentrations due to having no mechanical ventilation for ten hours of the day. The intermittent exhaust diverges from the continuous exhaust and has lower concentrations when it is off. The cycling of the CFIS and HRV systems are clearly observed. The higher air flow rates when operating lead to the higher peaks for these systems.

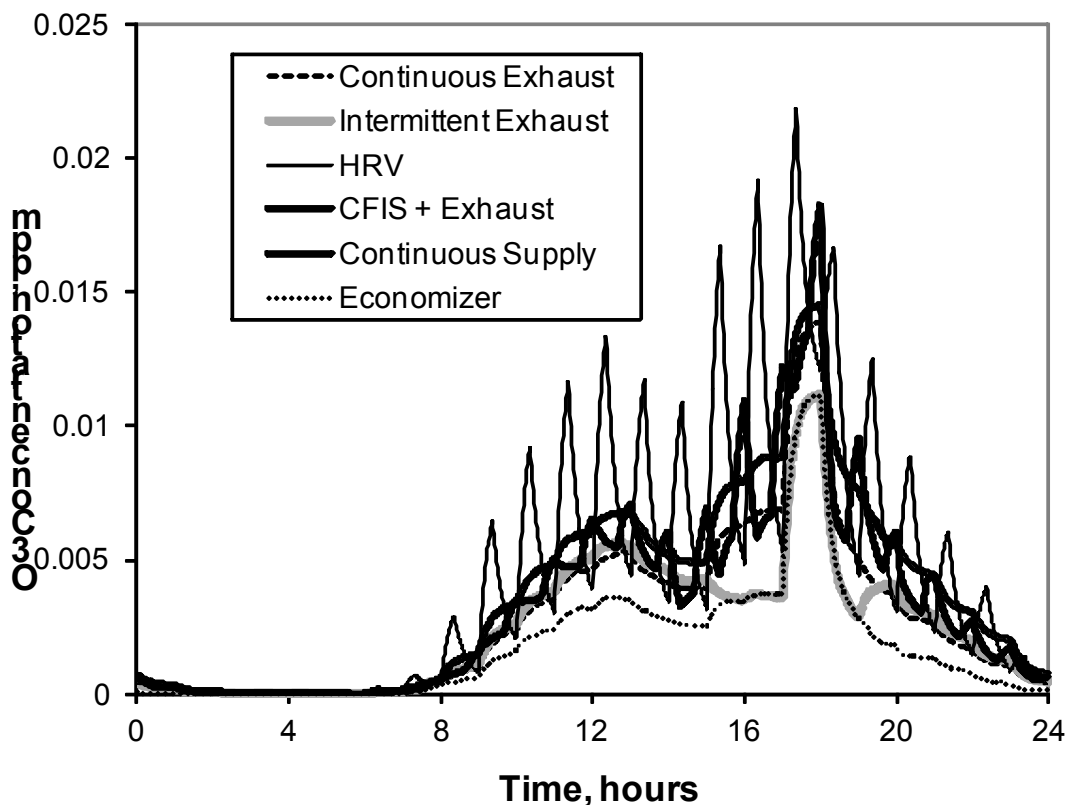


Figure 10. Comparison of indoor ozone concentration for different ventilation strategies in Riverside.

For each ventilation system, the average air change rate was calculated, together with the average indoor ozone concentration, the average indoor:outdoor concentration ratio (all over a 24 hour period) and the indoor peak. Table 1 summarizes all these results and shows that for all but the open windows case, the average indoor concentrations are below the 10 ppb that is considered a level of concern, and the better performing (from an ozone level perspective) ventilation systems have peaks that are close to 10 ppb. For comparison purposes, the outdoor peak and average concentrations are: 56 and 151 ppb for Riverside and 52 and 127 ppb for Livermore. Table 1 shows that the HRV produced the highest indoor ozone concentrations. This is due to a combination of having a higher air exchange rate than the unbalanced ventilation cases because balanced ventilation combine linearly adds with the natural infiltration through envelope leaks, but the supply and exhaust system air flows combine sub-additively. This higher air exchange brings more ozone into the home. The HRV and supply systems had higher peaks concentrations than the exhaust system because, while they had the same average mechanical air flow, they cycled on and off and had higher airflows when their fans were turned on. The intermittent exhaust deliberately ventilated less when the outdoor concentrations of ozone were highest, and this resulted in about a 10% reduction in indoor ozone concentrations. To be more useful, this strategy would need to be off for a longer period of time, or be used in a building with a tighter envelope where the natural infiltration with the mechanical ventilation system turned off would be lower. The open windows case was significantly higher in terms of both peak and average ozone (by more than a factor of five) because the air flow rates are high and air flowing in through an open window has no opportunity to be filtered by the envelope. This result for open windows is expected based on the

results of field testing discussed earlier. However, the internal deposition and forced air system filter removal mechanisms are still active and the indoor ozone levels are still much lower than outside. The best ventilation system performance is from the economizer. The economizer ventilates a lot at night when ozone concentrations are low and there mechanical ventilation system is off for ten hours of the day (10 a.m. to 8 p.m.) – thus avoiding ventilation through most of the significant outdoor ozone levels. Also, when operating, the economizer is a very high ventilation rate and can quickly dilute any remaining indoor ozone.

Table 1. Summary of air exchange rates and ozone concentrations.

Climate zone	Ventilation system	Average air exchange rate (h ⁻¹)	Average indoor ozone level (ppb)	Average indoor:outdoor ratio	Indoor peak ozone level (ppb)
10	continuous exhaust	0.33	2.8	0.053	13.9
	intermittent exhaust	0.33	2.5	0.047	11.0
	HRV	0.45	4.5	0.083	21.8
	CFIS+continuous exhaust	0.39	3.4	0.062	18.3
	continuous supply	0.30	3.7	0.068	14.5
	economizer	1.64	1.8	0.33	11.0
10	open windows	2.49	26	0.467	87
12	continuous exhaust	0.32	2.5	0.050	8.8
	intermittent exhaust	0.32	2.3	0.046	7.3
	HRV	0.44	4.2	0.083	16.2
	CFIS+continuous exhaust	0.38	3.0	0.059	11.4
	continuous supply	0.33	3.7	0.071	9.3
	economizer	1.42	1.4	0.029	7.3

The results show that in each case the indoor ozone concentrations are much lower than those outside, and that ventilation system selection can effect the indoor ozone concentrations by about a factor of three. The peak levels follow the same trends. The two key factors in selecting a ventilation system to minimize ozone levels are: 1. the envelope is good ozone filter, so systems that depressurize the house lead to lower indoor ozone levels, and 2., controls that allow ventilation systems to turn off during high outdoor ozone and ventilate more when outdoor ozone is low.

The above results – in terms of exact ozone concentrations are specific to the locations studies and other locations, with different outdoor ozone profiles would result in changes to indoor concentrations. Similarly the particular changes to indoor:outdoor concentrations will be influenced by home airtightness, weather, and home construction (material interactions with ozone and air flow paths). However, this study was focused on the effects of different ventilation systems, and their relative performance would be preserved for at different locations with changes in ozone, weather and building parameters. Therefore, the conclusions are limited to the relative merits of the ventilation approaches studied here rather than specifics about ozone concentration levels.

10. Conclusions and Recommendations

The following conclusions result from the modeling, simulation and analysis:

- Staying indoors with windows closed significantly (by 80% to 90%) reduces exposure to ozone - even when mechanical ventilation systems are operating due to a combination of envelope filtration and interior deposition.
- Open windows and the resulting unfiltered high ventilation rate significantly reduces the benefits of being indoors.
- Selection of ventilation systems can have a significant impact on indoor:outdoor ozone ratios:
 - Exhaust systems give lower indoor:outdoor ozone ratios (by about 20%) of ozone due to ozone filtration of incoming air in the building envelope.
 - Ventilation systems that can be turned off during high outdoor ozone events and operated at higher air flows at other times (to ensure other pollutants are adequately ventilated) can reduce indoor:outdoor ozone ratios significantly (by about 10-40%)
 - Ventilation systems that have high air flow rates while operating (and cycle off to maintain the same average air flow rate) can produce peak indoor concentrations about double those of other systems

Recommended future activities are:

- Investigate the use of optimized ventilation strategies and air tightening to mitigate indoor ozone
- Further examination of the byproducts of ozone reactions with building materials (such as insulation) and simulating the byproduct formation and indoor levels of byproducts from ozone-initiated chemistry
- Evaluation of the deliberate ozone removal using activated carbon filters integrated into ventilation systems

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