



## Passive reduction of human exposure to indoor ozone

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### ABSTRACT

Reactive building materials offer an opportunity to provide indoor air cleaning with minimal energy use. Laboratory and test house experiments provide evidence that indoor ozone concentrations can be diminished by activated carbon (AC) and unpainted gypsum wallboard (GWB) panels. These two materials are highly reactive with ozone and produce few byproducts. When measured in a 14.2 m<sup>3</sup> stainless-steel chamber, the mean deposition velocities to the materials were 5.3 m h<sup>-1</sup> for AC and 2.4 m h<sup>-1</sup> for GWB for a variety of airflow and relative humidity conditions. The ozone decay rates for both the materials were also measured in an unoccupied 34.5 m<sup>3</sup> bedroom under various mixing conditions. In this case, ozone removal increased relative to background by 27–100% with a 4.4 m<sup>2</sup> panel of a reactive material placed on one wall of the bedroom. The ozone decay rate for the bedroom increased over background by approximately 2–3 h<sup>-1</sup> for GWB and 2–7 h<sup>-1</sup> for AC. Application of a mass balance model for a typical home demonstrates that effectiveness for ozone removal depends weakly on the air exchange rate and strongly on the panel material, panel area, and mixing conditions. An ozone removal effectiveness of over 80% is possible with sufficient panel area and positioning that provides elevated air speeds near the panels.

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### 1. Introduction

Approximately 40% of American energy use is associated with buildings and, consequently, the US Department of Energy has set a goal to have net zero-energy residences by the year 2020. This will likely result in reduced ventilation rates and reduced implementation and use of heating, ventilation, and air conditioning (HVAC) systems. These energy-saving measures can directly or indirectly worsen indoor air quality. Without central HVAC systems, whole-house air cleaning by forced filtration is not viable. It is, therefore, important to design air cleaning strategies that do not rely on HVAC systems and do not contribute to building energy usage. Further, zero to low-energy air cleaning can help promote energy conservation in existing buildings regardless of the availability of HVAC systems.

Conventional strategies for reducing levels of indoor air pollution can be classified into three broad categories: source reduction, dilution by ventilation, and active engineered control systems (in HVAC systems or as stand-alone air purifiers). Ventilation has a substantial

energy penalty associated with fans and thermal conditioning and is responsible for approximately 25% of building energy use [1]. Similarly, effective traditional control systems require high airflow rates and consequent energy usage for fans. As such, reduction of pollutant emissions (source reduction) is generally considered the preferential strategy for improving indoor air quality whenever possible. However, many sources, such as those associated with necessary occupant activities, cannot be avoided and not all indoor air pollution originates indoors. For pollutants of outdoor origin, ventilation does not reduce indoor concentrations and may even increase them.

In this paper, we propose the use of passive control strategies that might be used to remove pollutants to indoor surfaces with minimal energy penalty. We explore the use of this strategy for lowering indoor ozone concentrations, where the ozone may originate outdoors or from indoor sources. Two passive removal materials (PRMs) were selected for study, activated carbon (AC) and unpainted gypsum wallboard (GWB). These materials have relatively high reactivity with ozone and should produce few byproducts [2–4]. Laboratory chamber and test house experiments were completed to determine ozone deposition velocities to AC and GWB over a wide range of air flow conditions. The relative effectiveness of using PRMs to reduce occupant exposures to ozone was then estimated using a mass balance model on a well-mixed residential home.

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## 2. Background

Exposure to ozone constitutes a human health hazard. Exposure decreases short-term lung function [5, 6], is linked to increased rates of asthma symptoms in infants [7], and is correlated with increases in morbidity and mortality rates [8]. Approximately 40–60% of ozone exposure occurs indoors [9, 10], and therefore minimizing indoor ozone concentrations is an important part of reducing total ozone exposure. Outdoor ozone concentrations are typically the dominant source of ozone in residences [11], and efforts to reduce concentrations of outdoor ozone precursors are time consuming and expensive. In addition, many indoor ozone sources exist, such as laser printers, photocopiers, and ion generators [12–15].

Surface deposition dominates indoor ozone removal and is typically modeled by the following equation [11]:

$$R = v_d CA \quad (1)$$

where  $R$  = removal rate of ozone to a surface ( $\mu\text{g h}^{-1}$ ),  $v_d$  = deposition velocity for ozone to a surface ( $\text{m h}^{-1}$ ),  $C$  = concentration of ozone in air above a surface ( $\mu\text{g m}^{-3}$ ), and  $A$  = area of surface on which ozone is depositing ( $\text{m}^2$ ).

The ozone deposition velocity to a surface encompasses the transport of ozone to the surface and the reactivity of a surface with ozone. The overall resistance to ozone removal at a surface is typically modeled as the sum of a transport resistance and a surface reaction resistance, as described by the following equation [16]:

$$\frac{1}{v_d} = \frac{1}{v_t} + \frac{4}{\gamma v_B} \quad (2)$$

where  $v_t$  = transport-limited deposition velocity ( $\text{m h}^{-1}$ ),  $\gamma$  = reaction probability (–), and  $v_B$  = Boltzmann velocity for depositing gas, in this case ozone ( $\text{m h}^{-1}$ ).

As indicated by Eqs. (1) and (2), three primary parameters influence the degree of ozone removal to a surface: the surface area of the reactive material, the fluid mechanics of the room and boundary layer adjacent to a material, and the reactivity of a material. Fluid mechanic conditions determine the transport-limited deposition velocity, which encompasses both transport from the source to the reactive material as well as boundary layer effects. The reaction probability is defined as the number of reactions that occur on a surface normalized by the number of collisions of molecules with that surface, and is used to characterize the reactivity of the surface. Ozone reaction probabilities for common building materials generally range from about  $10^{-7}$  to  $10^{-5}$ , with some highly reactive materials approaching  $10^{-4}$  [16, 17].

Homogeneous and heterogeneous ozone reactions with unsaturated organic compounds form a range of byproducts, including carbonyls, carboxylic acids, oxidized secondary organic aerosols, and other oxidized products [9, 18–20]. Many of these reaction products may be as harmful to human health as ozone itself [9]. Thus, any strategy to remove ozone by using reactive materials should strive for materials of high reactivity that produce negligible formation and release of harmful byproducts. Further, the material should be strategically placed to enhance the transport-limited deposition velocity ( $v_t$  in Eq. (2)).

## 3. Methodology

Chamber experiments were performed on an activated carbon mat and unpainted gypsum wallboard to determine ozone deposition velocities over a range of typical values of relative humidity. Both materials, as well as paperless gypsum wall board, were then analyzed in an unfurnished bedroom in a test house. For both

chamber and test house experiments, deposition to PRMs was determined for different air speeds induced by the use of portable fans and intended to represent a range of air speeds observed in typical residential environments.

### 3.1. Materials

A summary of the test materials used in this study is provided in Table 1. Experiments were conducted with activated carbon filtration media (AC), unpainted, paper-backed, gypsum wallboard (GWB), and unpainted paperless gypsum wallboard (PLGWB). The AC mat was constructed with a non-woven polyester base fabric (thickness = 0.5 cm) and coated with activated carbon, with an area-normalized mass of  $136 \text{ g m}^{-2}$ . For chamber and test house bedroom experiments, materials were cut to areas of 1.2 and  $4.4 \text{ m}^2$ , respectively, and the edges of the GWB (thickness = 1.3 cm) were sealed with aluminum tape.

### 3.2. Chamber experiments

Chamber experiments were performed in a  $14.2 \text{ m}^3$  stainless-steel chamber as depicted in Fig. 1. The gypsum wallboard was placed upright and flat against the wall. This prevented air from flowing behind the GWB. The AC was affixed to the wall of the chamber using aluminum tape on the edges. Because of the porous nature of the AC mat, some air may have penetrated into the volume of the mat.

Eight 12 V and variable-speed fans controlled by a variable DC power supply were mounted on two steel poles for mixing. Ozone concentrations were monitored using a dual beam UV-absorbance ozone analyzer (Model 205, 2B Technologies) placed outside of the chamber. Air was sampled from the chamber using polypropylene tubing (7 mm inside diameter and 2.5 m length) 2.1 m away from the PRM, affixed 1.4 m above the chamber floor to a steel pole. Carbon dioxide concentrations were measured using an infrared carbon dioxide analyzer (LI-COR Model LI-6252) for purposes of measuring chamber air exchange rates. For  $\text{CO}_2$  measurements, air was pulled from the chamber using the same type of tubing (4.6 m length) as for ozone measurements, and the analyzer was located outside of the chamber. Relative humidity (RH) was also monitored (TSI Q-Trak Model 8550), with the RH probe placed 40 cm above the chamber floor on one of the two steel poles that were used to mount fans. Air speeds were measured using an omnidirectional low-velocity sensor (Sensor Electronics, Model HT-428) placed 20 cm away from the center of the PRM.

For each experiment, ozone was generated by delivering pure oxygen to the ozone generator of a chemiluminescence  $\text{NO}_x$  analyzer (Thermo Electron Corporation Model 10). Ozone was injected into the chamber through polypropylene tubing until an initial concentration of 150–200 ppb was achieved. Carbon dioxide was injected into the chamber using a Tedlar<sup>®</sup> bag prefilled with  $\text{CO}_2$  until the chamber concentration reached approximately 500 ppm above background. Following the termination of injection, the concentrations of ozone and  $\text{CO}_2$  were recorded every 10 s until the ozone concentration reached 50 ppb. This procedure was

**Table 1**

Description of materials used for chamber and test house experiments.

Material	Scenario	Manufacturer	Model
AC	C, H	Gremarco Inc.	C0150
GWB	C, H	Georgia Pacific	Tough Rock
PLGWB	H	Georgia Pacific	Dens Armor Plus

C = Chamber; H = House; AC = activated carbon; GWB = gypsum wallboard; PLGWB = paperless gypsum wallboard.

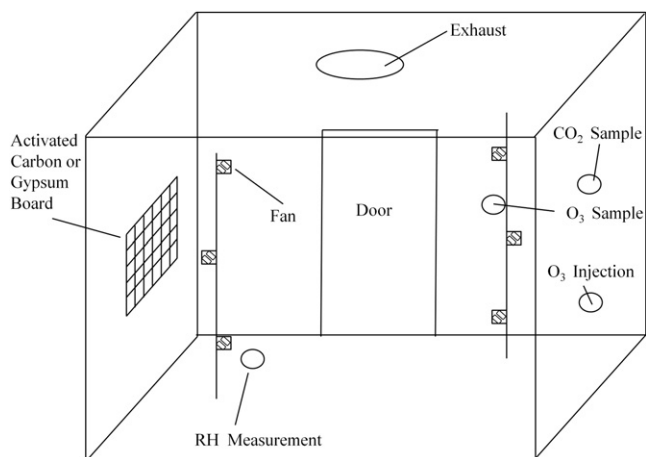


Fig. 1. Experimental configuration for chamber experiments.

conducted first with the chamber empty (no PRM) to assess the background ozone decay rate. A PRM was then affixed to a sidewall and the procedure was repeated on the same day, yielding a deposition velocity for the PRM.

Experiments were repeated at two different fan speeds. The average air speed was measured at both levels of mixing by placing the anemometer 20 cm away from the center of the PRM. Air speed measurements were taken every second for approximately 10 min and averaged.

### 3.3. Test house experiments

PRM experiments were completed in a bedroom in the UTest House located at the University of Texas at Austin. The bedroom has a floor area of 11 m<sup>2</sup> and a volume of 34.5 m<sup>3</sup>. It contained no furniture and had finished materials that consisted of vinyl flooring, painted gypsum wallboard for the walls and ceiling, two painted wood doors, one glass window, curtains, and painted wood molding.

Single PRM panels were mounted on one wall of the bedroom. The same types of activated carbon and gypsum wallboards were used as in chamber experiments. Paperless gypsum wallboard (PLGWB) was also tested to investigate the role of the paper and adhesive on ozone removal.

Activated carbon was affixed to the wall using aluminum tape. As in the chamber experiments, there may have been incidental airflow through the activated carbon mats due to their porous nature. The gypsum wallboard was held flat against the wall using mirror hangers, which prevented airflow behind the GWB panels. An area of 4.4 m<sup>2</sup> of each material was used for each test.

Experiments were completed with and without forced air mixing. Stand-alone multidirectional oscillating fans on high speed provided mixing for forced air conditions. However, the intent here is not to couple the use of fans and PRMs. Instead, fans were used during experiments to simulate air speeds that already occur in buildings at locations where PRMs might be placed, including near supply diffusers, ceiling fans, computer fans, south facing exterior walls, etc.

The same procedure was used for measuring air speeds in the test house as in the chamber, except speeds were averaged over three locations along the wall containing the PRM. A fourth air speed was measured near the center of the bedroom. Anemometer measurements along the wall were equally spaced and located at the same height as the approximate center of a PRM.

Five scenarios were considered as described below, and each test condition was completed with and without a PRM in order to assess the contribution of removal contributed by the PRM:

1. Empty room with no added mixing (no fans).
2. One non-oscillating fan in a corner of the room pointed away from the PRM.
3. One oscillating fan in the middle of the room pointed at the wall with the PRM.
4. Three oscillating fans approximately three feet from the wall containing the PRM.
5. Three non-oscillating fans directed at the PRMs.

Each of these five conditions was completed for activated carbon and gypsum wallboard. All but Condition 2 were completed for paperless gypsum wallboard. Generally, 3–4 repetitions were conducted for each background condition as well as for each PRM scenario.

Both carbon dioxide and ozone were injected into bedroom air and the decay in concentration of each chemical was monitored following injection to determine air exchange and ozone decay rates using procedures described below. An ozone generator (Yanco Industries Model OL80WT/FM100-k) was used to inject ozone into the room using 2.6 m of 7 mm inside diameter polypropylene tubing. A pure oxygen supply was used for ozone generation. Carbon dioxide was also introduced via 7-mm polypropylene tubing attached to the wire guard of a mixing fan to enhance the rate and degree of mixing during its introduction.

Ozone concentrations were measured using a single beam UV-absorbance ozone analyzer (2B Technologies Model 202) placed on a metal stand 0.6 m above the floor near the center of the room. Carbon dioxide was measured using an infrared CO<sub>2</sub> analyzer and data logger (Telaire Model 7001) affixed to a steel pole and mounted near the center of the room. Relative humidity and temperature were monitored using a sensor (Onset Computer Model Hobo U12) placed near the ozone monitor. Relative humidity and temperature ranged from 56% to 66% and temperatures ranged from 26 to 28 °C during test house experiments.

Airflow between the bedroom and the rest of the house was minimized by switching off the HVAC system, covering supply HVAC registers with tape, and sealing the door undercut by placing a cloth sheet under the door from the outside. The rest of the house was connected to the outside by opening all doors and windows. This served to minimize ozone and CO<sub>2</sub> exiting and reentering the bedroom.

Experiments to quantify background ozone decay rates were completed in the unfurnished bedroom with the existing painted drywall exposed. For the PRM cases, there was a concern that the PRM covered approximately 7% of the surface area of the room and would therefore diminish the background removal. Additional experiments were completed to explore this potential bias. Non-reactive Tedlar<sup>®</sup> sheets with the same area as the PRMs were placed on top of the bedroom's existing painted drywall and the three fan non-oscillating background and experimental cases (i.e., the cases with the largest possible effect) were repeated. Results with and without the Tedlar<sup>®</sup> sheets were within 1% of one another, thus validating the use of background decay rates for subsequent calculations.

To further assess the potential for ozone removal in areas of high mass transfer potential we completed several tests using a ceiling fan in the 42 m<sup>2</sup> living room and kitchen area of the UTest House. Slipcovers made of AC were used to cover the blades of an overhead ceiling fan. To keep the blades moving at the same speed with and without the activated carbon, non-reactive Teflon<sup>®</sup> covers were placed over the activated carbon covers. Then, ozone and CO<sub>2</sub> concentrations were measured in the same fashion as described for

the bedroom, but with the ceiling fan blades covered. The experiment was repeated three times with the fan at its maximum speed.

### 3.4. Determination of $v_d$

A well-mixed environment was assumed for both  $O_3$  and  $CO_2$ . Eq. (3) is based on a mass balance for either gas, assuming there are no emission sources of the gas, and homogenous gas-phase reactions are negligible.

$$\frac{dC}{dt} = -\lambda C + \lambda C_{out} - \frac{1}{V} \sum_i v_{d,i} A_i C \quad (3)$$

where  $C$  = concentration of gas in chamber or bedroom air (ppb),  $t$  = time (h),  $\lambda$  = air exchange rate ( $h^{-1}$ ),  $C_{out}$  = concentration of gas entering chamber or bedroom (ppb),  $V$  = volume ( $m^3$ ),  $v_{d,i}$  = deposition velocity of the  $i$ th material ( $m h^{-1}$ ), and  $A_i$  = surface area of the  $i$ th material ( $m^2$ ).

Irreversible deposition does not occur for  $CO_2$ , allowing for the solution of air exchange rate in accordance with the following equation:

$$\lambda t = -\ln\left(\frac{C - C_{out}}{C_0 - C_{out}}\right) \quad (4)$$

where  $C_0$  = the initial concentration of  $CO_2$  in the chamber or room air (ppb).

The air exchange rate was determined using a linear regression of the natural logarithm term versus time for each experimental run. Experimental error was determined from the larger of the instrument error or the standard error from the regression.

An ozone decay rate,  $\beta$ , is defined as the sum of deposition losses to the test environment background and PRM in the following equation:

$$\beta = \frac{v_{d,prm} A_{prm}}{V} + \frac{v_{d,c} A_c}{V} \quad (5)$$

where  $\beta$  = ozone decay rate ( $h^{-1}$ ),  $v_{d,c}$  = deposition velocity to the chamber or bedroom surfaces ( $m h^{-1}$ ),  $A_c$  = surface area of the chamber or bedroom ( $m^2$ ),  $v_{d,prm}$  = deposition velocity of the PRM ( $m h^{-1}$ ), and  $A_{prm}$  = horizontally projected area of the PRM ( $m^2$ ).

The deposition velocity for the PRM is set to zero in the absence of a PRM in the chamber or test house. To determine the ozone deposition velocities for the test environment and PRM, Eq. (3) was solved for ozone concentration, yielding Eq. (6). Experimental data were fitted to Eq. (6) for each scenario, with and without a PRM present, yielding  $\beta$  for each scenario. Knowing the horizontally projected surface area of each material and the volume of the room allowed for deposition velocities to be calculated in accordance with Eq. (5),

$$C = \frac{\lambda p C_{out}}{\lambda + \beta} \left[ 1 - e^{-(\lambda + \beta)t} \right] + C_0 e^{-(\lambda + \beta)t} \quad (6)$$

where  $p$  is the penetration factor for ozone (assumed to be 1 for these experiments). Uncertainties in the measured ozone decay rates for the background were based on a propagation of error analysis using the maximum of instrument error,  $\pm 2\%$  for the ozone analyzer and  $\pm 7\%$  for the  $CO_2$  analyzer, the standard error from the linear regression, or the standard deviation of all the background experimental runs for that mixing scenario. The uncertainties in the ozone decay rates for the PRMs were based on a propagation of error from the background error and the maximum of instrument error or standard error.

In order to put PRMs in the context of building occupant exposure to ozone, we calculated the effectiveness of removing

ozone in a typical residence. Ratios of indoor ozone to outdoor ozone were calculated by re-arranging Eq. (3) for  $C/C_0$ . This ratio was calculated for two scenarios: a hypothetical home with and without the presence of a PRM. The ratio of  $C/C_0$  with a PRM to  $C/C_0$  without a PRM can be used to determine an effective ozone removal that is independent of outdoor ozone concentration. This calculation was repeated while varying air exchange rates and area of experimental material. Based on the effectiveness for portable air cleaners defined by Miller-Leiden et al. [25], we define an effectiveness,  $H$ , using the following equation:

$$H = 1 - \frac{C^*}{C} \quad (7)$$

where  $C^*$  = steady-state indoor concentration of ozone with PRM present (ppb) and  $C$  = steady-state indoor concentration of ozone with no PRM present (ppb).

Eqs. (6) and (7) were solved with the following values for input parameters. A well-mixed house with an ozone penetration factor of 1 for flow through the building envelope was assumed. The ozone decay rate for a typical house was taken as the average ( $2.8 h^{-1}$ ) from a study of 43 residences [26]. The volume of a typical house was estimated by multiplying the average floor area,  $163 m^2$ , from US census data, by an assumed 2.5 m ceiling height [27]. We chose six PRM deposition velocities that span the range of measured values from the test house experiments described above: activated carbon with no fan, one oscillating fan, and three non-oscillating fans and gypsum wallboard with no fan, one oscillating, and three non-oscillating fans.

## 4. Results and discussion

Experimental results are presented below, first for laboratory chamber experiments and then for test house experiments. Results are then applied to a mass balance model for a typical home in order to determine the potential benefits of PRMs in terms of reduced exposure to ozone.

### 4.1. Chamber experiments

The mean and standard deviations of ozone decay rates over all empty chamber experiments were  $0.06 \pm 0.025$  and  $0.10 \pm 0.036 h^{-1}$  for low and high air speeds, respectively. Empty chamber decay rates were considerably lower than ozone decay rates when the chamber contained a PRM. The mean and standard deviations of ozone decay rates when an AC panel was placed in the chamber were  $0.39 \pm 0.041$  and  $0.53 \pm 0.098 h^{-1}$  for low and high air speeds, respectively. Values for GB were  $0.22 \pm 0.03$  and  $0.20 \pm 0.05 h^{-1}$  for low and high air speeds, respectively. Ozone decay rates for the empty chamber and chamber containing a PRM were used to back-calculate PRM-specific deposition velocities as described above.

The ozone deposition velocities for GWB and AC placed in the laboratory chamber are presented in Fig. 2. For each PRM data are plotted two air speeds, 10 and 19  $cm s^{-1}$ . Deposition velocities are plotted versus the relative humidity of chamber air.

The ozone deposition velocity for AC ranged from 3.8 to 8.0  $m h^{-1}$ . Mean deposition velocities were 4.5  $m h^{-1}$  at the low fan speed and 6.1  $m h^{-1}$  at the higher fan speed. This range encompasses an ozone deposition velocity of 5.8  $m h^{-1}$  reported by Grøntoft and Raychaudhuri [3] for activated carbon cloth placed in a small laboratory chamber under laminar flow conditions (air speed not provided).

The ozone deposition velocity for AC increased when the air speed was increased from 10 to 19  $cm s^{-1}$ . Such an increase indicates the importance of transport limitations on the overall deposition process, particularly for a highly reactive material such as

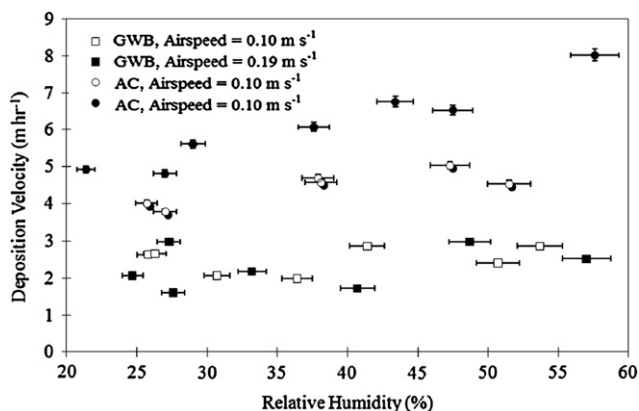


Fig. 2. Ozone deposition velocities for gypsum board and activated carbon placed in the experimental chamber at various values of relative humidity.

activated carbon. It also suggests the potential for enhanced removal of ozone if AC mats are placed in areas of elevated air speeds, e.g., in the thermal plume of occupants and electrical equipment, near air supply vents, or near overhead fans.

The ozone deposition velocity for AC also exhibited a dependence on relative humidity (RH) in the range of 20–60% RH. For both air speeds the deposition velocity increased with increasing RH, with the increase more pronounced at the higher air speed. This suggests that as transport limitations are reduced the presence of water on the AC may enhance surface removal of ozone. A similar but far less pronounced effect was observed by Grøntoft and Raychaudhuri [3] for activated carbon cloth. Others have found no effect or a negative effect of increasing RH on ozone removal to granular activated carbon [21, 22]. Lee and Davidson [21] observed that the efficiency of ozone removal to activated fiber filters decreased when relative humidity was increased from 20% to 50%. Additional research is needed to resolve these differing experimental observations.

Ozone deposition velocities for GWB varied between approximately 1.5 and 3 m h<sup>-1</sup>. This range is consistent with a value of approximately 2.5 m h<sup>-1</sup> reported for unpainted paperless GWB in a small laboratory chamber (air speed not provided) [4]. Grøntoft and Raychaudhuri [3] estimated ozone deposition velocities for unpainted gypsum wallboard of 4.3 and 5 m h<sup>-1</sup> based on experimental results for coarse composite panels. Kleno et al. [23] employed an FLEC cell to deliver ozone to the surface of GWB and measured ozone removal from FLEC inlet to exhaust. They determined an ozone deposition of 28.8 m h<sup>-1</sup>, an order of magnitude greater than results presented here or by others. We speculate that this may be due to a boundary layer that was not fully developed above the GWB in the smaller FLEC environment, thus leading to reduced transport resistance and greater ozone deposition.

In contrast to activated carbon, ozone deposition velocities for GWB were not affected by variations in either air speed or relative humidity. The mean deposition velocities were 2.5 ± 0.3 and 2.3 ± 0.6 m h<sup>-1</sup> at the low and high air speeds, respectively, and over the complete range of relative humidity. The lack of change in deposition velocity with increasing air speed suggests that surface reactions may be the more controlling factor to overall deposition of ozone to GWB, at least within the range of air speeds used for chamber experiments. The lack of dependence on RH suggests that molecular build-up of water on GWB does not greatly affect ozone surface reactivity for this PRM.

#### 4.2. UTest house experiments

The first set of experiments in the test house were completed with no fan in operation and lead to a mean air speed of

approximately 3 cm s<sup>-1</sup> above each PRM, a value less than those observed in the laboratory chamber (10 and 19 cm s<sup>-1</sup>). For comparison, Matthews et al. [24] observed mean air speeds in residences of 7.2–57 cm s<sup>-1</sup>. For AC and GWB, additional experiments were completed with a single non-oscillating fan pointed away from the PRM. The mean air speed adjacent to the PRMs for this case was 36 cm s<sup>-1</sup>. Three additional sets of experiments were completed with fans that directed air toward the PRM; one set was completed for each of the three PRMs. These sets were intended to simulate conditions in a real home where PRMs might be strategically placed in areas with sizeable air movement, e.g., near air supply vents or overhead fans. The mean air speeds adjacent to the PRMs in each of these cases were greater than those in the chamber, with values of 42 cm s<sup>-1</sup> (one oscillating fan), 75 cm s<sup>-1</sup> (three oscillating fans), and 156 cm s<sup>-1</sup> (three non-oscillating fans). These values are well within the range expected for air speeds near wall or ceiling supply diffusers and ceiling fans [28–30], underscoring the potential use of PRMs in existing buildings without auxiliary energy requirements.

As expected, for each set of experiments involving elevated air speeds in the test house the ozone deposition velocity to GWB or AC was much greater than observed in the laboratory chamber. For example, deposition velocities for 1 and 3 oscillating fans directed at the PRM in the test house were 24 and 27 m h<sup>-1</sup> for AC, compared to a maximum value of 8 m h<sup>-1</sup> to AC in the laboratory chamber. The value for three non-oscillating fans was 53 m h<sup>-1</sup>. It is likely that under these conditions there was greater air flow, and hence ozone penetration, into the mat canopy than occurred in the chamber, and thus greater removal of ozone. Since the deposition velocity is based on calculations using the horizontally projected area of the mat, ozone penetration into the mat and exposure to a greater surface area is manifested as a deposition velocity higher than that for air flow parallel to the mat surface. Nevertheless, enhanced ozone removal under such conditions should be possible if the AC mat is strategically placed in a position to take advantage of air flows into the PRM. Interestingly, even under no fan conditions the ozone deposition velocity to AC mat was 13 m h<sup>-1</sup>, approximately a factor of 2 greater in the test house than the laboratory chamber, despite lower air speeds in the test house.

Ozone deposition velocities to GWB were less affected by variations in air speed than were those for AC in the test house, results similar to those observed for the laboratory chamber. Deposition velocities increased from only 16 to 22 m h<sup>-1</sup> from the case of one oscillating fan to three non-oscillating fans. With no fan in use, the deposition velocity in the test house was 5.3 m h<sup>-1</sup>, as with AC approximately a factor of 2 greater than that observed in the chamber for GWB. The factor of 2 differences in deposition velocities may have been caused by a consistent difference in air flow or mixing conditions in the two systems.

In actual building environments ozone removal to surfaces is typically presented as decay rate, since this does not require evaluation of effective reactive surface area or volume. Ozone decay rates are also directly comparable to air exchange rates in units of h<sup>-1</sup>, and allow for simple subtraction of background decay. As such, we present the remainder of results for test house experiments as ozone decay rates.

Ozone decay rates for AC, GWB, and paperless GWB (PLGWB) are presented in Figs. 3, 4, and 5, respectively. Since each background measurement (without PRM) did not always directly correspond to a PRM measurement, we averaged multiple background measurements for each scenario. The error bars on the background readings correspond to the largest of instrument uncertainty, standard error, or the standard deviation between the background readings for that fan scenario. Similarly, the error bars for the PRM correspond to the maximum of instrument uncertainty or standard error for

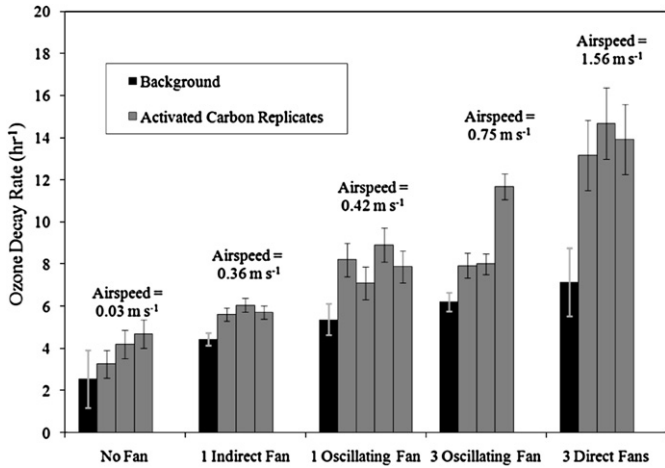


Fig. 3. Ozone decay rates for bedroom with 4.4 m<sup>2</sup> of activated carbon (AC) PRM placed on a vertical wall. Air speeds are listed above each set of bars.

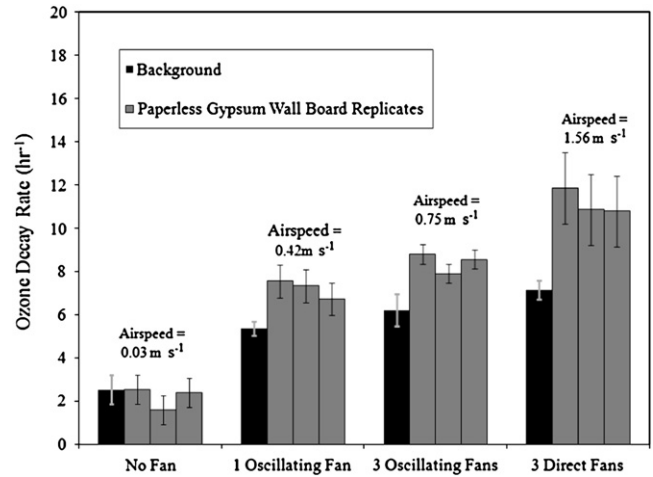


Fig. 5. Ozone decay rates for bedroom with 4.4 m<sup>2</sup> of paperless gypsum wallboard (PLGWB) PRM placed on a vertical wall.

only the PRM portion of the decay. Over all experiments the average background ozone decay rate increased with an increase in air speed. This is expected and consistent with a reduction in the transport resistance term (increase in transport-limited deposition velocity) in Eq. (2) as air speed in a room or near a PRM increases.

The ozone decay rate for a 4.4 m<sup>2</sup> AC mat increased with an increase in the number of fans and corresponding increase in air speeds (Fig. 3). These results are consistent with the dependence of ozone deposition on air speeds observed for chamber experiments, again demonstrating the importance of transport resistance to ozone deposition. The results for three oscillating fans exhibited much more variation than the other cases. The scatter may have been due to differences in airspeeds depending on initial fan position within the oscillation leading to different air speeds on the PRM.

The ozone decay rate for GWB was on average 56% that of AC (Fig. 4). The results for PLGWB (Fig. 5) are similar to those for GWB. The ozone decay rate was on average only 12% higher with PLGWB compared to GWB, suggesting that in the cases with GWB much of the deposition occurs on the actual gypsum material and not on the exterior layer of paper.

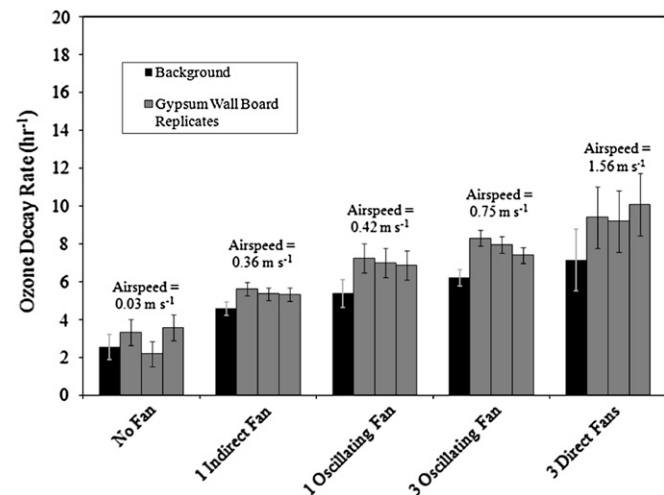


Fig. 4. Ozone decay rates for bedroom with 4.4 m<sup>2</sup> of gypsum wallboard (GWB) PRM placed on a vertical wall.

An increase in air speed over the GWB increased the ozone decay rate, but to an extent less pronounced than for AC. Ozone decay rates decreased slightly, relative to background decay rates, with GWB and PLGWB for one repetition each in the no fan scenario. Tests for these PRMs in the no fan scenario were within the uncertainty of the measurements. All else being equal, the GWB appears to be similarly reactive to the surrounding painted wallboard of the room. Since the deposition velocity is more sensitive to air speed than the surrounding surfaces of the room, it is likely that the addition of a PRM might have affected the boundary layer or airflow conditions, and thus decreased the transport-limited deposition velocity. These cases highlight the importance of fluid mechanics on ozone removal in some room configurations.

The predicted ozone removal effectiveness versus air exchange rate for eight 4.4 m<sup>2</sup> PRM panels in a typical US home is presented in Fig. 6. Effectiveness ranges from 8% to 10% for the no-fan deposition velocity and GWB to 55% to 60% for AC with three oscillating fans. Varying the air exchange rate over an order of magnitude has only a 10–20% effect on ozone removal effectiveness. This is due to the fact that the sum of the background ozone loss and the loss to the PRM are much larger than the loss due to air exchange and

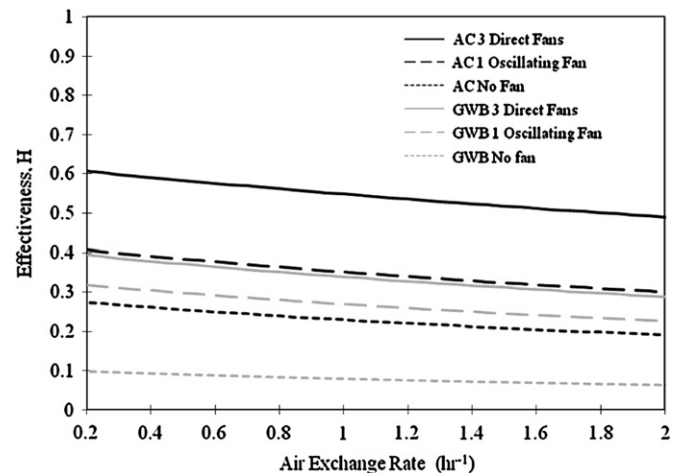


Fig. 6. Effectiveness, *H*, as a function of air exchange rate for a typical residence with a PRM area of 36 m<sup>2</sup>.

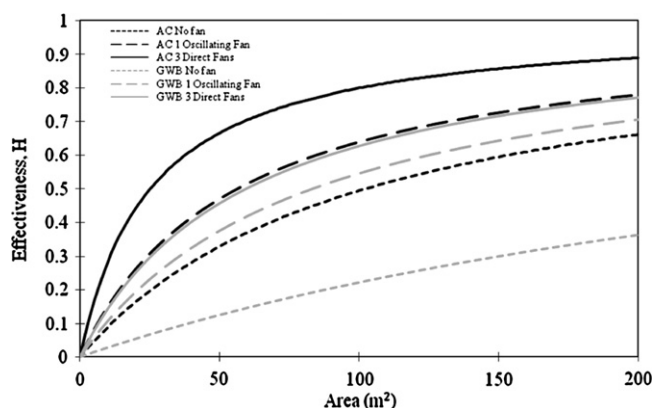


Fig. 7. Effectiveness versus area of PRM for a typical residence with air exchange rate =  $0.5 \text{ h}^{-1}$ .

suggests that PRMs are applicable to a wide range of US housing, including naturally ventilated buildings. Although effectiveness can be small for GWB without optimization for air movement, the fact that ozone is being removed with no energy input into the building suggests that the concept of PRMs is worthy of further exploration.

The ozone removal effectiveness versus the area of PRM for the US median air exchange rate of  $0.5 \text{ h}^{-1}$  [31] is presented in Fig. 7. Results indicate that an effectiveness greater than 80%, a benchmark often cited for portable air cleaning devices [32], is achievable for activated carbon that is placed in areas with elevated air speeds. Under such conditions, an ozone removal effectiveness of 50% is possible with as little as  $25 \text{ m}^2$  of AC, approximately 2–3% of the total floor, ceiling, and wall area of a typical house. In the case without any additional source of air movement, an effectiveness of 50% is achievable with approximately  $120 \text{ m}^2$  of AC mat placed on indoor surfaces (no fan case for AC in Fig. 6). As expected, adding PRM area increases ozone removal effectiveness, with diminishing marginal benefit as the PRM area becomes large.

During the ceiling fan experiments, we measured a mean increase in ozone decay rate of greater than  $1 \text{ h}^{-1}$ , or about 33% above background, when activated carbon mat covered the fan blades compared with Teflon<sup>®</sup> fan blades. This provides further evidence that taking advantage of existing areas with high mass transfer holds promise for increasing the ozone removal effectiveness of PRMs.

## 5. Closure

With movement toward lower energy housing, indoor air quality can suffer as a result of low ventilation rates. We propose a low-energy method for removing gas phase indoor pollutants. The concept was proven for removing ozone with two passive reaction materials (PRMs), activated carbon, and unpainted gypsum wallboard. Ozone removal rates increased over background, particularly under conditions of elevated air speeds, by placing  $4.4 \text{ m}^2$  of PRM in an unoccupied bedroom. Preliminary analysis suggests that for a typical American residence an ozone removal effectiveness of over 50% can be achieved by using highly reactive PRMs such as activated carbon mat, with higher values of removal effectiveness possible if the PRM is placed in an area with high air speeds, e.g., near supply vents. Model results suggest that passive removal can be an effective method for reducing exposure to ozone by as much as 25–50% of total daily exposure.

In this paper, we focused on the effectiveness of activated carbon and gypsum wallboard for the removal of ozone. Many other

materials, however, have the potential to be used as PRMs. For example, unsealed concrete has been observed to react with ozone and not produce large quantities of harmful byproducts [33]. Furthermore, many pollutants other than ozone are of concern indoors. The concept of passive removal should be explored as a strategy to control all indoor pollutants, not simply ozone. For example, formaldehyde, an important indoor pollutant, is removed by wool [34], albeit with a need for periodic renewal. Similarly, a composite material effectively removed formaldehyde passively in chamber tests and in a field study in Japanese residences [35]. Moriske et al. [36] explored the use of a wall paper coated with activated carbon on its backside and observed that removal of ozone by the carbon can reduce indoor formaldehyde concentrations. Thus, PRMs hold promise as a means of reducing exposure to several important indoor pollutants. Additional research is needed to study optimal placement of PRMs in residential and commercial buildings, to better understand the coupling of fluid mechanics and chemistry on pollutant removal to PRMs, including the effects of these processes on concentration gradients near PRMs, and to explore the long-term reactivity, capacity, and costs of different PRMs under actual field conditions.

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