

Passive Ozone Control Through Use of Reactive Indoor Wall and Ceiling Materials

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Donna A. Kunkel, Richard L. Corsi, Atila Novoselac, Jeffery A. Siegel, Glenn C. Morrison

Department of Civil, Architectural and Environmental Engineering
The University of Texas at Austin
10100 Burnet Road (R7100, Bldg 133)
Austin, TX 78758, USA

ABSTRACT

Most ozone exposure occurs indoors even though some surfaces consume ozone and reduce its concentration relative to outdoors. Ozone consumption often results in emissions of secondary pollutants. But materials such as gypsum board (drywall) and activated carbon show promise as ozone consumers without generation of oxidized organic contaminants. In this study, we evaluated activated carbon and unpainted drywall as passive ozone control surfaces in a room-sized laboratory chamber. Mean deposition velocities were 2.4 m hr^{-1} for gypsum board and 5.3 m hr^{-1} for activated carbon. The deposition velocity was measured at two mean air velocities of 0.1 and 0.19 m s^{-1} and over a relative humidity range of 25 to 55%. The reactivity of gypsum board was independent of relative humidity. An increase in relative humidity, from 20-50%, resulted in increased reactivity for activated carbon. In our model for a typical house, about 35% of the wall space would need to be replaced with unpainted drywall, or 12% with activated carbon to reduce indoor ozone concentrations by 50%.

INTRODUCTION

Ozone exposure has been linked to negative health effects, such as decreased pulmonary function,¹ increased rates of asthma symptoms in infants,² and increases in morbidity and mortality. Specifically, an increase of 10 ppb outdoor ozone concentration has been linked to an increased mortality rate of 0.87%.³ Ozone is thought to primarily affect the respiratory system through reactions with the lining of the lungs⁴. Since Americans spend, on average, over 90% of their time indoors,⁵ it is estimated between 25 and 60% of ozone exposure occurs indoors.⁶

Ozone reacts with a multitude of building materials, gas phase pollutants, and even occupants themselves⁶. Building materials vary widely in their uptake of ozone. Uptake rates for ozone are often reported as a deposition velocity, v_d , which has been thoroughly discussed⁷. The deposition velocities with respect to ozone for numerous building materials have been published. Of particular interest to the indoor environment, carpet

has an average deposition velocity of 2 m hr^{-1} , painted walls and ceilings have a deposition velocity of approximately 0.3 m hr^{-1} .⁸

Ozone reactions with typical indoor surfaces may come with negative consequences. Surface reactions produce byproducts, some of which are stable, such as some organic acids and carbonyls. A multitude of unstable products are also formed which have been discussed in detail in previous studies.⁶ Secondary organic aerosols have also been shown to form from ozone chemistry⁹. Many of these products are known to cause negative health effects in humans. Minimizing indoor ozone concentrations reduces the generation of these harmful by-products, as well as direct ozone exposure.

For any given well-mixed room, the ratio of the indoor to outdoor concentration of a surface reactive species (in this case, ozone) at steady state is given by:

Equation 1.

$$\frac{C}{C_{out}} = \frac{\lambda}{\lambda + \frac{1}{V} \sum v_{d,i} A_i}$$

where:

C = indoor concentration (ppb)

λ = air exchange rate (hr^{-1})

C_{out} = outdoor concentration (ppb)

$v_{d,i}$ = deposition velocity associated with surface i (m hr^{-1})

A_i = area of material i on which deposition is occurring (m^2)

V = volume of the room. (m^3)

Therefore, we propose to use commercially available materials to reduce indoor ozone concentrations. By replacing surfaces that have a low deposition velocity, such as painted walls, with surfaces that have larger deposition velocities, we are increasing the second term in the denominator. This corresponds to lower indoor ozone concentrations. Thus, these “passive reaction panels” (PRPs) can significantly reduce indoor ozone concentrations without the energy expenditure of other control mechanisms. Promising materials for this application include unpainted gypsum board and sheets of activated carbon fabric media, which have been shown to be highly reactive with ozone.^{10,11} Researchers using a FLEC emission cell measured a deposition velocity of 28.8 m hr^{-1} for unpainted gypsum board.¹⁰ Gypsum board backing was found to have a deposition

velocity of about 2 m hr.^{-1} .¹² Commercially available activated carbon filters, designed for an HVAC system were found to have removal efficiencies for ozone of over 90%.¹³

The ability of materials to consume ozone may be influenced by relative humidity, which varies widely depending on weather conditions as well as occupant activities. It is important to determine if differences in relative humidity affect the ability of activated carbon and gypsum board to be used as ozone sinks. When evaluating the impact of relative humidity on the ozone uptake of activated carbon, researchers found either no increase in reactivity or a decrease in reactivity, with a rise in relative humidity from 20% to 80% depending on the specific type of activated carbon used.¹³ The effect that relative humidity has on the reactivity of gypsum board has not yet been studied. Previous research has focused on passing air through or directly over activated carbon and gypsum board. We know of no investigations that have evaluated the materials in a passive sense, by simply placing the materials in a room with no intentional flow over them.

Our goal is to identify materials that may be used to passively remove ozone buildings. Our specific objectives are 1) to measure the deposition velocity of ozone on gypsum board and activated carbon under typical residential room conditions and 2) to characterize the effect that relative humidity has on the materials' ability to absorb ozone.

EXPERIMENTAL METHODS

Materials

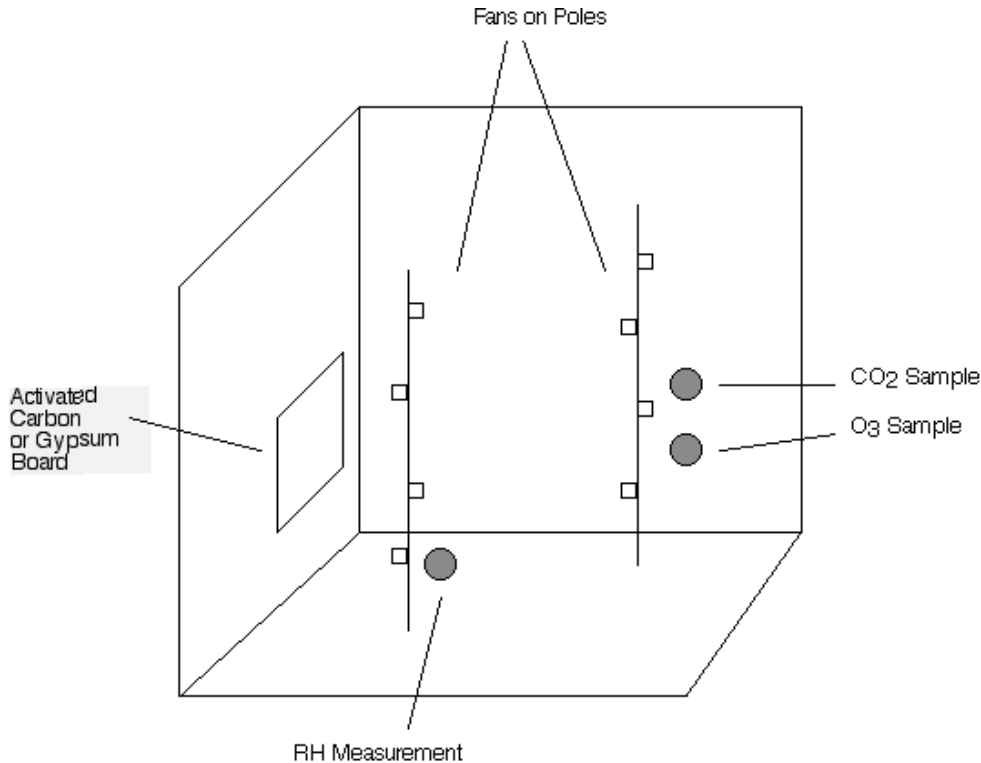
Two PRP materials were evaluated: activated carbon filtration media and unpainted gypsum board. Activated carbon filtration media, model C0150, was acquired from Greमारco Industries, Inc. It consisted of a non-woven polyester base fabric and a coating of activated carbon, with a weight of 135.7 g/m^2 . It was cut into a sheet with an area of 1.24 m^2 . The size was decided by the width of the activated carbon sheets and the width of the gypsum board. Unpainted gypsum board, also cut to an area of 1.24 m^2 , was acquired from a local hardware store. It was approximately one year old and had been stored stacked and exposed to ambient lab conditions. The edges of the gypsum board were covered in an aluminum tape to minimize any edge effects. Ozone was generated using a Thermo Electron Corporation Model 10 Chemiluminescent NO-NO₂-NO_x analyzer.

Experimental apparatus

All experiments were conducted in a stainless steel chamber with sides of length of 2.42 m. A room-sized chamber was selected to more accurately reflect conditions in a typical indoor environment. Eight, 12 V computer fans were wired to a variable DC power supply. The fans were hung from two metal freestanding poles to provide mixing for the room. Oxygen was passed through the ozone generator to pump ozone into the chamber. A dual beam ozone monitor (2B Technologies model 205) was used to measure ozone decay. A LI-COR carbon dioxide analyzer, model LI-6252, was used to record CO₂

decay. Relative humidity was monitored using a Q-trak (TSI, Inc, model 8550). See Figure 1 below for the experimental setup.

Figure 1: Experimental chamber, location of PRP, sensors, fans and gas sample locations.



Analytical measurements

The ozone monitor logged concentrations every 10 s, until the end of the experimental run. The data were then transferred to a computer.

CO₂ was manually injected into the chamber before the start of each experiment. The CO₂ analyzer logged CO₂ concentration every 10 s, and then sent the data to a computer for analysis.

Humidity was measured for each experimental run. The Q-trak was placed in the chamber with the measuring wand elevated to a few feet off the ground. The sampling was begun at the same time as ozone and CO₂ measurements were begun. The average relative humidity was noted at the end of each experiment.

To determine mean air velocity in the chamber, a Thermoanemometer Transducer (Sensor Electronic, model HT-428) was placed 20 cm away from the wall that was used for placement of activated carbon and gypsum board. The fans were set to a certain voltage, ranging from 6-12 V, and the air speed and turbulence were recorded for approximately 10 minutes. The mean and standard deviation of air velocities and turbulence were recorded.

Procedure

Ozone was elevated to approximately 200 ppb and carbon dioxide raised to about 300 ppm above background. Both gases were then switched off and all monitoring equipment began logging the data. The decays of ozone and CO₂ were recorded first for the empty chamber. From this, the chamber reactivity could be calculated as described below. On the same day, activated carbon was affixed to a sidewall using aluminum tape. The same procedure was followed with respect to raising the ozone and CO₂ concentrations and logging the data. After about an hour, the activated carbon was removed from the chamber and placed in the laboratory. Gypsum board was then placed in the same place where the activated carbon had been hung, and the procedure was repeated once more.

These experiments were performed at both the high and low fan speed. The experiments were conducted several days per week for 5 weeks. This helped to reduce systematic error and also served to determine if the materials were changing over time. Two to three replicates for each material, fan speed, and approximate relative humidity were performed. Only at high relative humidity was this not fully accomplished because there were few days when the ambient relative humidity reached those levels.

Determination of v_d

To determine the deposition velocity of ozone to activated carbon and gypsum board, a series of ozone decay experiments were performed. A well-mixed reactor model was assumed for the chamber. In this model, the governing equation for any pollutant is given by:

Equation 2. Mass balance for a well-mixed building environment.

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

It is assumed that there are no emission sources, and that gas phase reactions or other sinks are negligible. It is also assumed that no ozone is lost in entering the building envelope.

In this study, we determined both the air exchange rate and deposition of ozone to the materials by performing tracer decay of CO₂ and monitoring the decay of an injection of ozone. Using the above equation for CO₂ and noting that CO₂ does not irreversibly deposit to surfaces ($v_{d,i} = 0$) simplifies the equation. Solving for λ results in:

Equation 3. Air exchange rate from carbon dioxide decay.

$$\lambda = \frac{-\ln(C/C_o)}{t}$$

where:

C_o is the initial concentration of CO₂.

Likewise, solving Equation 2 for ozone, where ozone is removed at chamber surfaces and the passive reaction panel, yields Equation 4.

Equation 4. Summed surface removal rate (h⁻¹) for ozone with multiple surfaces

$$\frac{v_{d,c}A_c}{V} + \frac{v_{d,prp}A_{prp}}{V} + \lambda = \frac{\ln(C/C_o)}{t}$$

where:

$v_{d,c}$ = deposition velocity to chamber (m h⁻¹)

A_c = area of chamber (m²)

$v_{d,prp}$ = deposition velocity to PRP (m h⁻¹)

A_{prp} = area of PRP (m²)

For a measured air exchange rate (Equation 3), the area-averaged deposition velocity of ozone to the chamber, $v_{d,c}$, is determined without a PRP in place (that is, $A_{prp} = 0$) and then $v_{d,prp}$ is determined from a separate experiment with the PRP in place. For both CO₂ (Equation 3) and ozone (Equation 4), the loss term was determined by finding the slope of natural log of C/C_o versus time.

RESULTS AND DISCUSSION

Figures 2 and 3 show the deposition velocities for both materials vs. relative humidity at both air velocities. Mean air velocities were measured as 0.1 (Low) and 0.19 (High) m h⁻¹. The mean deposition velocities at the low and high fan speeds were 2.5 ± 0.3 m hr⁻¹ and 2.3 ± 0.6 m hr⁻¹ respectively for gypsum board. Activated carbon's deposition velocity increased with increased relative humidity, and ranged from 3.8 m hr⁻¹ to 8.0 m hr⁻¹, with averages of 4.5 m h⁻¹ (Low) and 6.1 m h⁻¹ (High).

For both materials, and gypsum board in particular, the results exhibited substantial scatter. There are many possible reasons for the scatter. The materials were possibly

exposed to contaminants between experiments in the chamber, since they were left open to ambient lab conditions. The air exchange rate also changed slightly during the experiments. While this effect was small, it could contribute some to the observed scatter. The deposition velocities for both materials were plotted versus time to determine if the scatter was due to the materials aging. There was no relationship between deposition velocity and age of the material.

Researchers previously found gypsum board backing to have a deposition velocity of just over 2 m h^{-1} ¹² and unpainted gypsum board to have a deposition velocity of 28.8 m hr^{-1} .¹⁰ Our average values of 2.3 and 2.5 m h^{-1} are very similar to the backing study. Deposition velocities are highly dependant on airflow conditions. The study with the large deposition velocity was conducted in a small, FLEC emission cell. Their reported values far exceed anticipated indoor transport-limited deposition velocities and the FLEC method may significantly enhance transport-limited flux relative to typical indoor surfaces. Another study found activated carbon to have a deposition velocity of approximately 4.9 m h^{-1} .¹³ This falls within our range of values. While deposition velocities are dependent on flow conditions, and the specific type of gypsum board or activated carbon sampled, these values provide a good confirmation that our numbers are plausible.

Relative humidity strongly influenced the deposition velocity for activated carbon, but there was no clear relative humidity impact on the reactivity of the gypsum board. The relationship between relative humidity and activated carbon was found by fitting the data with the linear regression solver from Microsoft Excel. There was a clear positive increase in the reactivity of the activated carbon with respect to relative humidity. Both sets of data were fit to the equation $y = a + bx$. For the low fan speed, a and b are given by:

$$a = 3.05 \pm 0.46 \text{ m hr}^{-1}$$
$$b = 0.03 \pm 0.01 \text{ m hr}^{-1}$$

At the high fan speed, a and b are given by:

$$a = 2.97 \pm 0.42 \text{ m hr}^{-1}$$
$$b = 0.08 \pm 0.01 \text{ m hr}^{-1}$$

Figure 2: Deposition Velocities for an Average Air Speed of 0.10 m/s

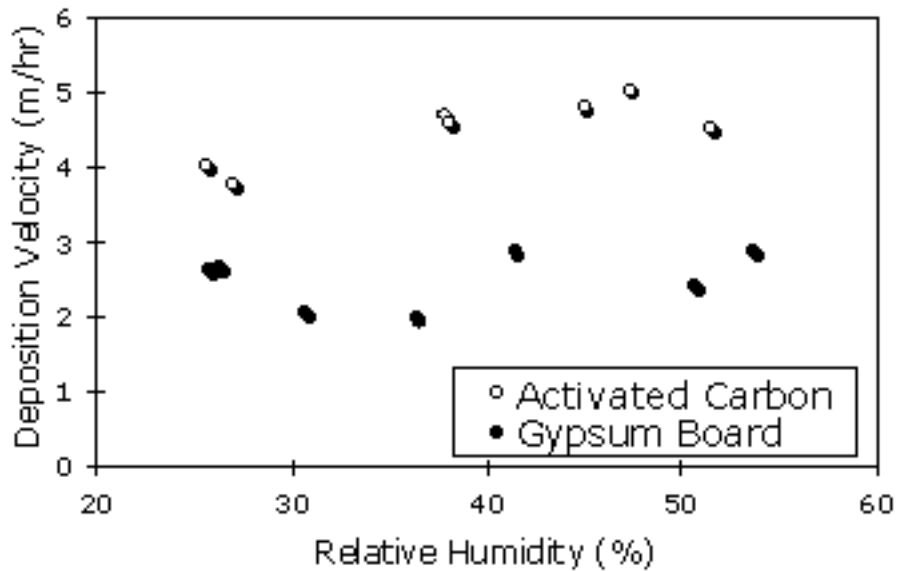
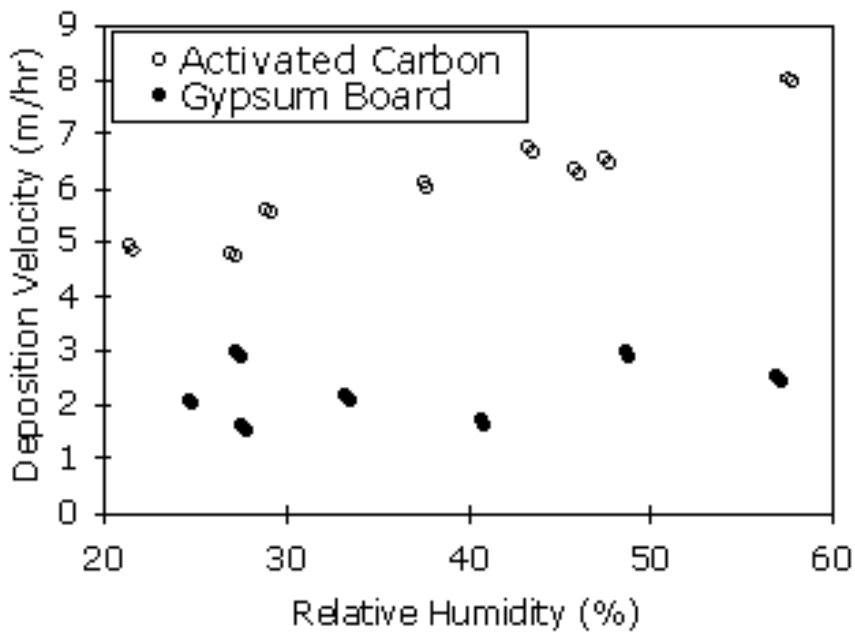


Figure 3: Deposition Velocities for an Average Air Speed of 0.19 m/s

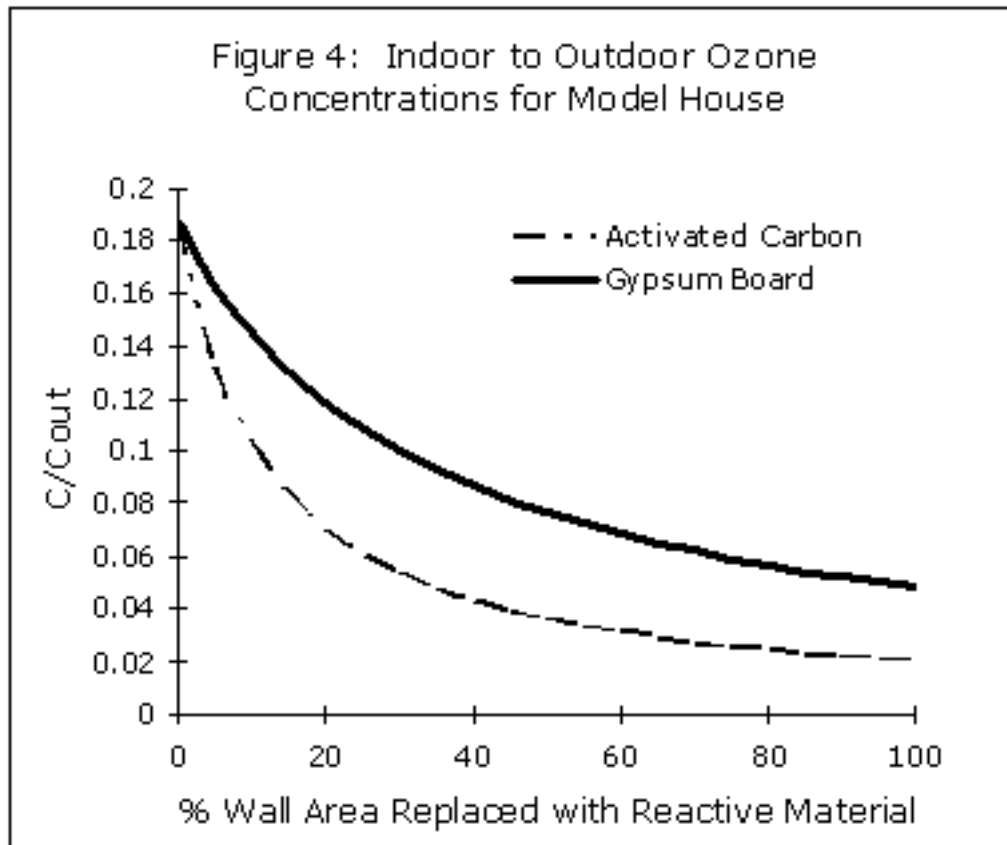


Whether or not the reactivity continues to increase with relative humidity or reaches a peak then decreases remains to be determined. This is in contrast to a previous study that found an increase in relative humidity from 20-80% resulted in either no impact or a decrease in the reactivity of activated carbon, depending on the specific material tested.¹³

One potential complication for the use of activated carbon is that volatile organic compounds (VOCs) adsorb to activated carbon. When non-reactive organics adsorb to activated carbon, its ability to remove ozone is decreased. When reactive VOCs adsorb to activated carbon, its ability to remove ozone is initially increased and subsequently is decreased.¹⁴ However, the relationship between VOC loading and ozone removal has only been determined at VOC concentrations that are much higher than commonly found indoors. More research is necessary to determine the effect that VOCs would have in a typical indoor environment.

To apply these results to a real situation, we simulated what effect replacing various amounts of walls with gypsum board or activated carbon would have on indoor to outdoor ozone ratios, using Equation 1. We assumed a surface area to volume ration of 3.75 m^{-1} , which falls in the typical range seen in American homes.¹⁵ We assumed a house that was unfurnished and consisted of a carpet and painted walls and ceilings. Also, we assumed that all ozone penetrates from outdoors. Carpet has an average deposition velocity of 2 m hr^{-1} , and painted walls and ceilings have a deposition velocity of 0.3 m hr^{-1} .¹⁶ For this model, we assumed an average air exchange rate of 0.5 hr^{-1} , which is typical for an American home.¹⁷

Below is a plot of the ratio of indoor to outdoor ozone concentration as wall material is replaced with activated carbon or gypsum board.



To reduce ozone concentration in our model home by 50%, about 12% of wall material would need to be replaced with activated carbon or 35% of wall material for gypsum board.

Practically, unpainted gypsum board could be used as a ceiling tile material in the construction of new homes. Activated carbon has the potential to serve as a way to retrofit already built houses. The aesthetics of activated carbon may not be suitable for most people to simply place on their walls. Future work needs to be done to design an aesthetically pleasing way to place activated carbon in areas of high mass transfer. By determining where mass transfer is high, such as around window frames, one could minimize the surface area required for the same decrease in ozone. In addition, more research is necessary to fully determine the longevity of these materials at the concentrations typically seen in buildings.

SUMMARY

Both activated carbon and gypsum board have shown great potential to be used as passive controls of ozone indoors. Mean deposition velocities were 2.4 m hr^{-1} for gypsum board and 5.3 m hr^{-1} for activated carbon. Relative humidity was not found to have an effect on the reactivity of gypsum board. Activated carbon's deposition velocity increased with an increase in relative humidity and ranged from 3.8 m hr^{-1} to 8.0 m hr^{-1} . More research is

needed to determine both the aesthetics of using activated carbon and the longevity of these materials for indoor ozone control.

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KEY WORDS

deposition velocity, drywall, activated carbon, gypsum board, ozone, building materials