

Ozone-Initiated Secondary Emission Rates of Aldehydes from Indoor Surfaces in Four Homes

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Field experiments were conducted in four homes during summer to quantify ozone-induced secondary emission rates (SERs) of aldehydes on indoor surfaces. Four surfaces in each house were examined: living room carpet, living room wall, kitchen floor, and kitchen counter. Upon exposure to ozone for 3 h, formaldehyde and C₃–C₁₀ saturated aldehydes, especially nonanal, were emitted as products of ozone–surface reactions. Carpet in newer homes had higher SERs than carpet in older homes. For example, the nonanal SER from the living room carpet was 80 $\mu\text{g m}^{-2} \text{h}^{-1}$ in a 1 year old home, but only 8–20 $\mu\text{g m}^{-2} \text{h}^{-1}$ in two homes that were greater than 10 years old. All kitchen countertops were very reactive and high SERs were observed, especially for nonanal. Product yields from countertops were consistent with the products of ozone reactions with oleic and linoleic esters, common in cooking oils. These findings suggest that carpet surfaces become depleted of reactants as they become oxidized over time. However, countertop surfaces, which are cleaned frequently or become covered in cooking oils, are continuously replenished with reactants. Over time, countertops may become the dominant contributor to indoor concentrations of secondary aldehydes. However, when total surface area is taken into account for the homes assessed, carpet is predicted to be the primary source of secondary emissions, even for older homes.

Introduction

Building furnishings and consumer products can be important sources of volatile organic compounds (VOCs) in indoor environments. Secondary emissions of VOCs, defined as emissions resulting from chemical transformations, can also increase the concentrations of odorous and irritating compounds (1–4). In this research, we study the secondary emissions of carbonyl compounds that result from ozone interactions with surfaces in four homes.

Weschler et al. (1) were the first to show that ozone reacted with an indoor surface (carpet) to form formaldehyde, acetaldehyde, and C₅–C₁₀ aldehydes. They proposed that the source of these carbonyl compounds was the reaction between ozone and unsaturated compounds coating or comprising carpet surfaces. Reiss et al. (2) showed that carbonyl groups (aldehydes and ketones) were formed as a result of latex paint exposure to ozone. Morrison and Nazaroff showed secondary aldehydes, especially nonanal, were the result of the reactive chemistry of ozone with duct materials

(3) and carpet (4). They found evidence that carpets were coated with unsaturated fatty acids, or nonvolatile polymers with some degree of unsaturation. They anticipated that these surface precursor compounds would eventually become depleted as ozone oxidized the limited number of unsaturated bonds in the coating.

Secondary emissions from new carpets may diminish as carpets age and lose their ability to react with ozone (5). While some surfaces age, kitchen countertops and other surfaces may become *more* reactive as a result of occupant activities. Nazaroff and Weschler (6) explained that many cleaning agents and air fresheners contain chemicals that can react with ozone on surfaces to yield potentially harmful secondary products. Wang et al. (7) found that during the normal use of consumer products such as soaps and oils, which are composed of unsaturated fatty acids and esters, indoor surfaces become covered with chemically reactive species that will emit aldehydes in the presence of ozone. They suggested that these daily use products regenerate the reactivity of indoor surfaces. The replenished surfaces may eventually replace carpet as the dominant contributor to secondary emissions. To our knowledge, there are no published reports quantifying ozone-initiated secondary emission rates (SERs) from indoor surfaces in field homes. The objective of the present study is to evaluate surface aging and regeneration by quantifying SERs from a variety of indoor surfaces in four homes.

Materials and Methods

Study Homes. Three single-family houses and one apartment in Rolla, Missouri were included in the study. Homes H1, H2, H3, and H4 were constructed 1, 2, 10, and 14 years, respectively, before the field experiments. Home H3 is a one-story apartment. Homes H1, H2, and H4 are two-story detached family houses. All furnishings are original and match the age of the home. Characteristics of the four homes and descriptions of tested surfaces are listed in Table 1.

In each home we evaluated the living room carpet or rug, living room wall, kitchen floor, and kitchen countertop. All living rooms were furnished with wall-to-wall carpeting except for home H2, which was furnished with hardwood floors and loose area rugs. For this home, the loose living room rug was tested. In addition, a loose kitchen rug and a dining room rug were tested in homes H2 and H3, respectively. SER experiments were conducted once on each surface in each home.

The air exchange rate was measured using a photoacoustic infrared analyzer (INOVA 1302) to measure SF₆ decay (8). With all doors and windows closed and the recirculation fan operating, approximately 1 L of SF₆ was introduced into the center of the living room. Then SF₆ was measured every minute at the same location. We observed that with the recirculation fan operating, it took less than 30 min following injection for the tracer to be well-mixed throughout each home. We used data collected 30 min after injection to evaluate the air exchange rate.

SER Experiments. SERs of aldehydes formed by reactions between ozone and various surfaces were measured using the apparatus shown in Figure 1. The system consisted of an ozone generator, humidifier, field emission chamber, sampling system, and an ultraviolet light photometric ozone analyzer (Teledyne model 400A). The 4.25-L Teflon-coated field emission chamber is open on the bottom so that it can be positioned on an indoor surface, isolate a defined area of the surface, collect emissions, and deliver reactants to that surface. Chamber dimensions, materials of construction, and

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TABLE 1. Characteristics of Four Homes and Their Surfaces

parameter	H1	H2	H3 ^a	H4
age (y)	1	2	10	14
volume (m ³)	505	560	175	810
carpet area (m ²)	170	73 ^b	53	228
kitchen countertop area (m ²)	2.6	3.3	1.8	4.9
kitchen floor area (m ²)	12.4	80.2	10.6	26.6
wall area (m ²) ^c	282	404	90	450
air exchange rate (h ⁻¹)	0.36	0.14	0.84	0.22
R ² of tracer decay	0.994	0.995	0.990	0.955
living room carpet	nylon cut pile carpet	hardwood floor covered with wool rugs	nylon cut pile carpet	nylon cut pile carpet
carpet pile height (cm)	1.0	1.2	0.9	1.0
living room wall	latex paint	latex paint	latex paint	latex paint
kitchen floor	ceramic tile	ceramic tile	vinyl	hardwood floor
kitchen countertop	resin ^d	laminated	laminated	resin
kitchen rug		polypropylene rug		
dining room rug			polypropylene rug	
laboratory experiments				
	carpet I		carpet II	
pile height (cm)	1.0		0.7	
material	polyester		cashmere	

^a One-story apartment. ^b Home H2 carpet area includes the loose living room rug and any other carpeted surfaces. ^c The ceiling is not included in wall area. ^d Resin countertop (nonporous surface) is a solid surface material made from acrylic resin (PMMA) and mineral filler (aluminum trihydrate).

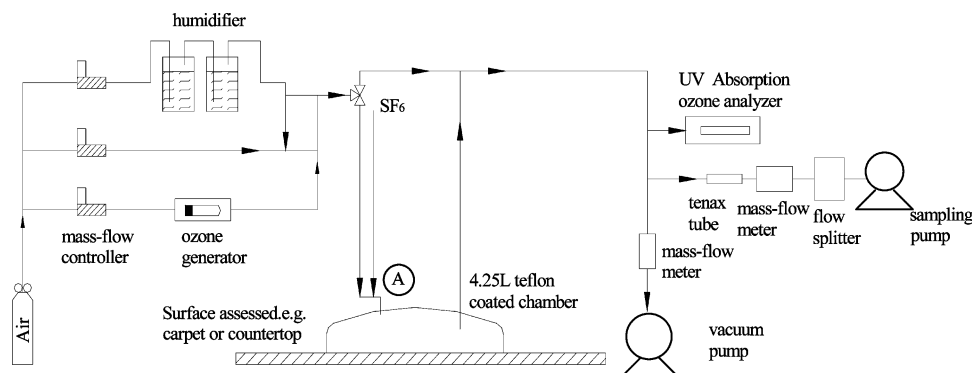


FIGURE 1. Experimental apparatus for measuring ozone-induced secondary emission rates from in-use surfaces. SF₆ was injected into the inlet branch at position A and the concentration decay was measured at the exhaust to determine the actual gas exchange rate.

methods of isolating the tested area are provided in the Supporting Information. Compressed air was introduced into the system and split among three streams. The air stream was passed through a humidifier (two gas sparging bottles, filled with distilled water, in series) before being mixed with an additional stream to produce air with a relative humidity of 50±5%. The third air stream passed through an ozone generator and then mixed with the humidified air. The chamber was continuously ventilated at 2.0 ± 0.01 L min⁻¹ of either humidified air or humidified air containing ozone. A Teflon three-way valve located at the inlet of the chamber was used to redirect the inlet flow so that either the inlet or outlet ozone concentrations could be measured. A vacuum pump was used at the exhaust stream to balance flow through the chamber.

Higher molecular weight target carbonyl compounds (C₅–C₁₀) were collected on sorbent tubes containing Tenax-TA. Two Tenax-TA samples were collected side-by-side at the exhaust. One sample was analyzed with GC-FID to quantify emission rate. The other sample was analyzed using a GC-MS to identify any nontarget compounds. Sample flow rates were 0.1 L min⁻¹. Sample volumes were 2.0 L. Ozone is known to either react with Tenax or with some analytes on the surface of Tenax, interfering with analyses (9). In prior work, we observed little loss of aldehydes on Tenax (4). Additionally, we found that higher molecular weight aldehydes tended to

adsorb to the surface of ozone scrubber materials, reducing recovery. Thus, ozone scrubbers were not used upstream of Tenax tubes. Without a scrubber, ozone reacts with Tenax to form nonanal. Thus, we subtracted the average nonanal mass formed, at that ozone concentration, from the nonanal mass collected on each sampling tube.

Lighter carbonyl compounds (C₁–C₄) were collected using cartridges (Supelco) filled with dinitrophenylhydrazine (DNPH) coated silica gel. The cartridge incorporates an ozone trap to eliminate carbonyl losses on the silica gel surface. Sample flow rates were 0.5 L min⁻¹. Sample volumes were 30 L.

An SER experiment was initiated (time *t* = 0) by ventilating the chamber with ozone-free air. From *t* = 0.5 h to *t* = 1.5 h, a DNPH sample was collected at the exhaust so that the sample was centered at *t* = 1 h. Similarly, two Tenax tube samples were collected at the exhaust with the sample interval centered at *t* = 1 h. Two duplicate Tenax tube samples were collected immediately after these samples. These samples were used to quantify the primary emissions from the surface in the absence of ozone. Starting at *t* = 1.5 h, ozone was introduced into the chamber at a mixing ratio of 100–150 ppb. After the surface was exposed to ozone for 0.5 h, a DNPH and two Tenax samples were collected at times centered on *t* = 1 and 3 h after initiating ozone exposure. These samples were used to determine SERs of the reaction between ozone

and the surface. A final sample was obtained at the chamber inlet as a system inlet blank. Inlet and outlet ozone concentration measurements were used to determine the ozone deposition flux to the surface. To test indoor air VOC concentrations, DNPH and Tenax samples were collected 1 m above the floor in the main living area of the homes at least 1 h after turning on the recirculation fan.

System Leak Test. Field emission chambers that are intended to seal onto a surface (instead of completely enclosing a surface sample) may leak around the point of contact between the chamber and the surface, especially if the surface is not smooth. The leak test conditions were the same as those for the SER measurements, except that the photoacoustic infrared analyzer was positioned at the exhaust. A known mass of SF₆ was injected into the inlet at point A, as shown in Figure 1. Assuming the system acts as a completely mixed flow reactor, the gas exchange rate was determined from the rate of decrease of the concentration of sulfurhexafluoride during a 0.5 h period (8). The percent leakage was determined by comparing the % difference between the estimated and measured gas exchange rates. The system was considered ready to use if the leakage was less than 5%.

Chemical Analysis. Analytes collected on Tenax-TA sample tubes were analyzed using an autosampler thermal desorption system attached to a gas chromatograph with a flame-ionization detector (TD/GCFID). Tubes were desorbed at 140 °C for 10 min. The TD cold-trap was then desorbed at 150 °C delivering the analytes to the GCFID. The GC inlet pressure was 101 kPa with a total gas flow rate of 7.3 mL min⁻¹, operated in split-less and constant pressure modes. The oven temperature was initially set at 50 °C and held there before increasing at a rate of 30 °C min⁻¹ up to a maximum temperature of 250 °C. The FID was set at 250 °C with gas flows as follows: hydrogen, 40 mL min⁻¹; compressed air, 450 mL min⁻¹; and nitrogen, 45 mL min⁻¹. Calibration standards for C₅–C₁₀ saturated aldehydes and 2-nonenal were made from pure standards (Sigma-Aldrich). Mass calibration was achieved by injecting methanol-diluted standards directly onto clean sorbent tubes and analyzed using TD/GCFID. The analysis of indoor air VOCs was performed using a thermal desorption system attached to a gas chromatograph with a mass spectrometer (GCMS), equipped with an Agilent 122-7033 capillary column (30 m, 0.25 mm i.d., 0.5 μm film thickness). Individual aldehydes were quantified using the same standards as used in the TD/GCFID system. Lightweight aldehydes were analyzed with HPLC. Batches of cartridges were prepared based on EPA method TO-11A (10). Analytes were identified and quantified using dinitrophenylhydrazone standards. We found that an unidentified reaction product interfered with our analysis of acetaldehyde, and we therefore do not report results for this compound.

Laboratory SERs for Carpet. To test the assumption that the ozone reaction on indoor surfaces is a first-order process (11), we challenged two different carpet samples to four different ozone levels (0, 170, 320, 400 ppb) under conditions otherwise identical to those used for field experiments. Reaction products were collected to determine SERs. Carpet sample information is shown in Table 1.

Results

Secondary Emission Rates. With the high air exchange rate of 30 h⁻¹, product formation rates from surfaces were anticipated to be much greater than the product formation rates due to homogeneous gas-phase reactions (12). Therefore, results are reported in terms of the analyte mass emission rate per exposed surface area (μg m⁻² h⁻¹). SERs were obtained by subtracting the primary emission rates from the 3 h emission rates. Although SER measurements were obtained at 1 and 3 h after initiating ozone exposure, we observed that

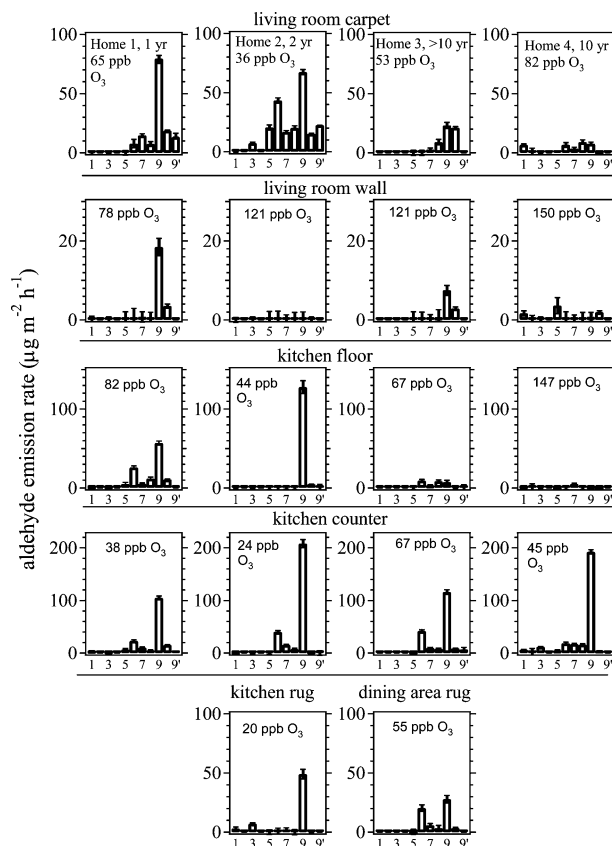


FIGURE 2. Secondary aldehyde emission rates for each studied surface in four homes. Category axis numbers correspond to the number of carbons in aliphatic aldehydes except for 2-nonenal, which is denoted 9'. C₁, C₃, and C₄ aldehydes were not shown for H3 results because DNPH samples were not collected.

the 3 h SERs were about 60% higher than the 1 h SERs. We only report the 3 h results here as they better reflect steady-state conditions. Figure 2 shows the ozone-induced SERs for C₁ and C₃–C₁₀ aldehydes. Acetaldehyde is not included, due to uncertainty in identification. C₁ and C₃ aldehydes are not shown for home H3 because DNPH samples were not collected. Each of the four columns of plots represents a home—respectively, homes H1, H2, H3, and H4. In the first four rows are shown the SERs from living room carpet, living room wall, kitchen floor, and kitchen counter, respectively. The fifth row shows the results of additional tested surfaces: kitchen rug in H2 and dining room rug in H4. Outlet ozone mixing ratios at the end of each experiment are listed in the figure. Uncertainty bars represent error propagation of the standard error of calibrations and replicate experiments for each surface.

Ozone interactions with indoor surfaces resulted in increased emissions of C₁ and C₃–C₁₀ saturated aldehydes. Living room carpets in homes H1 and H2 also emitted 2-nonenal, denoted 9' in Figure 2. SERs of individual aldehydes ranged from less than the method detection limits (MDL), for most aldehydes emitted from walls, to 208 μg m⁻² h⁻¹ for nonanal emitted from kitchen countertop in home H2. Nonanal was the most prominent secondary aldehyde emitted from any surface. Although the number of homes tested was small, SERs from carpet and kitchen floor in new homes appear to be substantially higher than that from older homes. The living room carpet SER of nonanal in home H1 was 80 μg m⁻² h⁻¹, but only 8 μg m⁻² h⁻¹ in H4. The kitchen floor SER of nonanal in home H2 was 127 μg m⁻² h⁻¹ but only 1.8 μg m⁻² h⁻¹ in H4. Most of wall SERs were below the MDL. The highest SER for formaldehyde was observed for H4 living

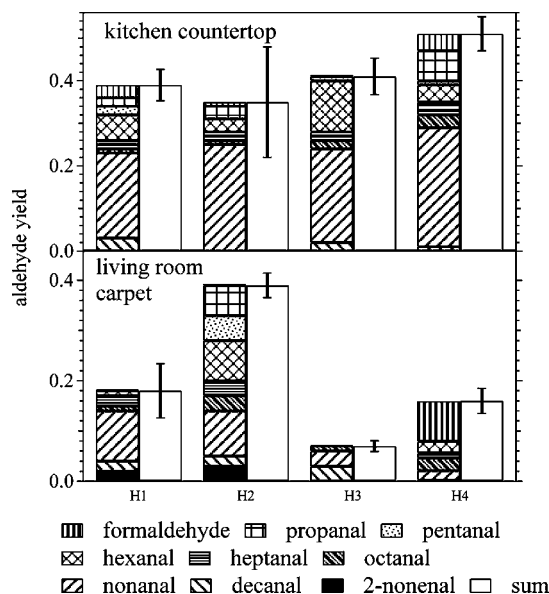


FIGURE 3. Ozone-induced aldehyde yields for kitchen countertop and living room carpet.

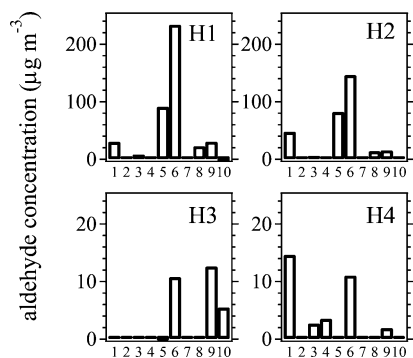


FIGURE 4. Indoor aldehyde concentrations in each home. C₁, C₃, and C₄ aldehydes are not shown for H3 because DNPH samples were not collected.

room carpet ($6.75 \mu\text{g m}^{-2} \text{h}^{-1}$). High SERs generally corresponded to lower outlet ozone mixing ratios.

Yields. The “yield” represents the reaction product yield, based on the assumption that SERs are proportional to ozone deposition rates. The yield is defined as the ratio of the molar SER to the molar flux of ozone to that surface. Shown in Figure 3 are yields for C₁, C₃–C₁₀ aldehydes from kitchen countertop and living room carpet in H1, H2, and H4. Yields for C₅–C₁₀ aldehydes are shown for H3. Typically, the nonanal yield for countertop was ~ 0.2 , indicating 20% of the deposited ozone produced nonanal. The summed formation for all target aldehydes ranged between 0.07 and 0.51.

The emission patterns are qualitatively similar among countertops of different houses indicating that the surfaces are covered with similar reactants that produce primarily nonanal and hexanal. The emission patterns are qualitatively different between kitchen countertop and living room carpet. In home H2, nonanal accounted for 71% of the total molar SER from the countertop, but only 23% of the total molar SER from living room carpet. This suggests that the composition of surface reactants differs between carpets and countertops.

Indoor Aldehyde Concentration. The concentrations of aldehydes in indoor air are shown in Figure 4. New homes had higher levels of lower molecular weight aldehydes than older homes. The high formaldehyde, pentanal, and hexanal levels may come from newer manufactured wood products. Hodgson et al. (13) observed relatively high formaldehyde,

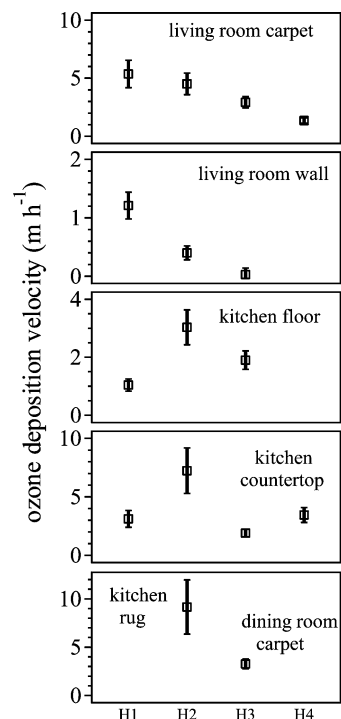


FIGURE 5. Ozone deposition velocity for each surface.

pentanal, and hexanal concentrations in a newly built home and ascribed these to primary emissions from plywood subfloor, passage doors, and cabinetry. Even though secondary nonanal yields are highest on new home carpet, other aldehydes are observed at the highest concentrations in air. Primary emission rates appear to dominate secondary emission rates in newer homes.

Deposition Velocity. The ozone deposition velocity is a mass transfer coefficient that, for these experiments, acts as a relative indicator of the reactivity of surfaces. The ozone deposition velocity (v_d) was determined from the experiments by modeling the field emission chamber as an ideal continuously mixed flow reactor (CMFR) (14) as follows:

$$v_d = \frac{QC_{inlet} - (Q + v_{d,c}A_c)C_{outlet}}{AC_{outlet}} \quad (1)$$

where Q is the volumetric flow rate through the reactor, A is the surface area of the material, A_c is the inner surface area of the chamber, C_{inlet} is the inlet ozone concentration and C_{outlet} is the outlet ozone concentration. The inherent reactivity of the chamber, parametrized by the chamber surface deposition velocity, $v_{d,c}$, was determined beforehand in the lab (0.40 m h^{-1}).

Deposition velocity results are shown in Figure 5. Materials with higher surface aldehyde emission rates tended to have higher ozone deposition velocities. The highest ozone deposition velocity (7.2 m h^{-1}) was measured on the H2 kitchen countertop where we observed the highest SERs of aldehydes. We also observed a tendency for the deposition velocity on carpet to decrease from the newest home H1 to the oldest home H4. This may be due to ozone “aging” of carpet as observed by Morrison and Nazaroff in laboratory chamber experiments (5). Our observed range of values for the oldest to the newest carpet (1.4 – 5.4 m h^{-1}) falls within the range observed by Morrison and Nazaroff for heavily exposed carpet (1.4 m h^{-1}) and a freshly exposed carpet (6.1 m h^{-1}). The range of values is in the high range estimated for carpets installed in a building (0.3 – 6.5 m h^{-1}) (15), probably because the large air exchange rate of the field emission cell engenders higher transport rates. Similarly, the

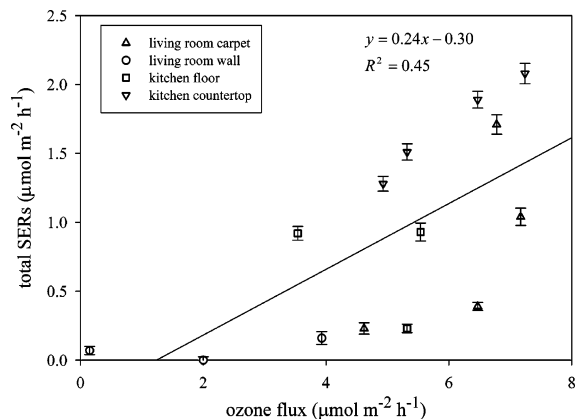


FIGURE 6. Total aldehyde molar emission rates for all surfaces as a function of ozone flux.

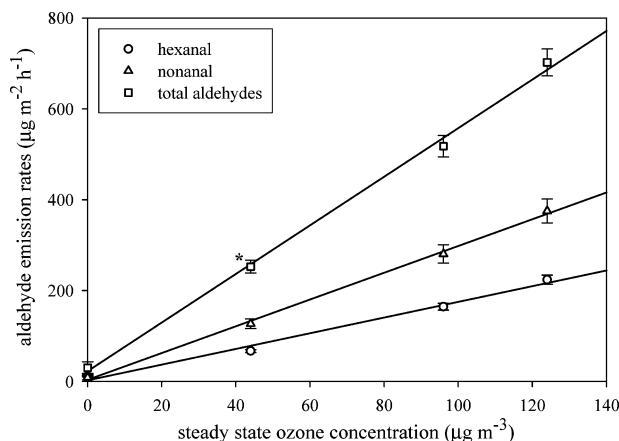


FIGURE 7. Secondary hexanal, nonanal, and total aldehyde emission rates for carpet surfaces as a function of steady-state residual ozone concentrations. The asterisk (*) denotes that C₁, C₃, and C₄ aldehydes were not included for these data points.

maximum deposition velocity for kitchen countertops (7.2 m h⁻¹) was near the maximum anticipated for very reactive surfaces in buildings (~8 m h⁻¹) and high local shear stress.

Figure 6 shows the relationship between the total secondary aldehydes molar emission rates and ozone flux for all tested surfaces. Ozone flux correlates with the summed aldehyde molar emission rates with a slope of 0.24 ± 0.076. The slope corresponds to an overall aldehyde yield of 0.24, which compares well with the average value from Figure 3 of 0.16. The intercept shown may indicate that ozone is consumed by reactions other than those that form aldehydes, or that we are not quantifying all reaction products.

First Order Reaction. Figure 7 shows the relationship between the steady state, residual ozone concentration, and the SERs for hexanal, nonanal, and total aldehydes. We observe that SERs increase linearly with the ozone concentration. We also observe a linear relationship between ozone flux and SERs. Therefore, the ozone–surface reaction appears to be first order. Further, the product yields reported for these experiments are independent of the residual ozone concentration.

Discussion

Secondary Emission Rates. Total SERs of aldehydes from living room carpet in new homes, of the order of 250 μg m⁻² h⁻¹, are comparable to or higher than ozone-induced SERs from prior carpet studies (4). However, the SERs from the carpet in older homes were significantly lower than those in new homes. It has been suggested that vegetable-based oils, which contain unsaturated fatty acid esters such as esters of

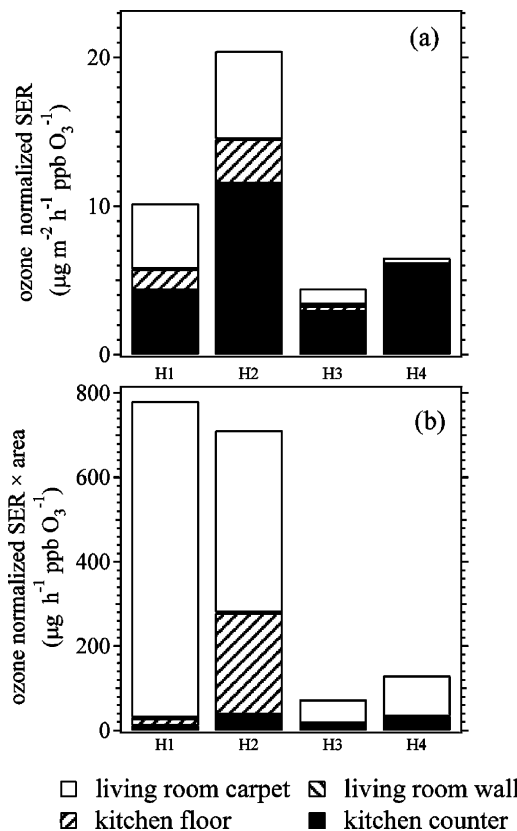


FIGURE 8. Normalized aldehyde emission rates for four homes.

linolenic, linoleic, and oleic acids, are responsible for the SERs of nonanal and hexanal from carpets or other indoor surfaces (4, 16). With time, the older carpet surfaces of H3 and H4 appear to have become depleted of these reactive oils. The results confirm that 2-nonenal, an unsaturated aldehyde with a low odor threshold, is the product of ozone chemistry with new carpets (H1 and H2) as observed by Morrison and Nazaroff (4). This compound was believed to be released as ozone reacting with modified forms of vegetable oils in which double-bond positions have been shifted by processing (4). Moise and Rudich (17) suggested that this compound may be formed in when ozone reacts with unmodified linoleic acid. However, 2-nonenal was not observed in the reactions with countertops that are expected to be coated with linoleic acid from cooking oils (7) or in ozonation experiments with linseed or tung oils (4).

We observed relatively high SERs from countertops of all homes, matching the laboratory findings of Wang et al. (7). They found similar emission rates and emission patterns from countertops coated with cooking oils. The relatively high nonanal and hexanal SERs suggest that the countertops are coated with oleic and linoleic acids or esters. Within limits, we would expect that the more a kitchen is used for cooking, or is cleaned, the higher the SERs will be from kitchen surfaces. From interviews with occupants we found that, qualitatively, the H2 kitchen was used most frequently for cooking among the four homes. This is in keeping with the finding that nonanal SERs from the H2 kitchen countertop was the highest among all homes. Unlike living room carpet, the SERs of nonanal from countertops in new homes are of the same order of magnitude as that in older homes. Daily use of consumer products, including oils and cleaners, appear to regenerate the surface, continuously supplying unsaturated fatty acids or triglycerides. This suggests that, in time, kitchen countertops, or other frequently cleaned surfaces, may replace carpet as the dominant contributor to indoor SERs of aldehydes.

Normalized Secondary Emission Rates. To understand which surface in each home contributes most to SERs, we determined the ozone normalized SER as shown in Figure 8a. The ozone normalized SER was obtained by dividing the summed aldehyde SERs with the outlet ozone concentration ($\mu\text{g m}^{-2} \text{h}^{-1} \text{ppb O}_3^{-1}$). This puts the SER for each surface on the same basis for comparison since the chamber ozone concentration varied among experiments. From H1 to H4, the total ozone normalized SER for carpet decreases for older homes. Normalized, kitchen countertops are much stronger emitters than carpet in older homes.

To consider how the actual area of these surfaces influences total emissions, we multiplied the ozone normalized SER by the superficial surface area of each surface from Table 1 to obtain Figure 8b. Compared in this manner, carpet remains the dominant contributor of SERs in new and old homes.

SERs were very low or undetectable from some walls and kitchen floors. This is in keeping with the low ozone uptake rates. However, high primary emission rates of lighter aldehydes in homes H1 and H2, as evidenced by high indoor concentrations, may have obscured low SERs. It is also possible that the primary emissions of adsorbed species were still relatively high during the 1 h initial sampling period, biasing the calculated SERs to lower values. We also observed that the 3 h SER was generally higher than the 1 h SER. This suggests that products may adsorb strongly to indoor surfaces in field homes, delaying the approach to steady state.

Implications For Indoor Air Quality. To estimate the increase in aldehyde concentrations due to secondary emissions, we applied a material-balance model (4)

$$C_{\text{aldehyde}} = \frac{v_d C_{\text{O}_3} \gamma A}{\lambda V} \left(\frac{MW_{\text{aldehyde}}}{MW_{\text{O}_3}} \right)$$

where C_{aldehyde} is the steady-state aldehyde concentration increment due to ozone reactions at an indoor surface ($\mu\text{g m}^{-3}$), v_d is the ozone deposition velocity (m h^{-1}), C_{O_3} is the steady-state ozone concentration ($\mu\text{g m}^{-3}$), γ is the aldehyde yield, A is the specific surface area (m^2), λ is the air exchange rate (h^{-1}), V is the building volume (m^3), MW_{aldehyde} is the molecular weight of the aldehyde (g mol^{-1}), and MW_{O_3} is the molecular weight of ozone (g mol^{-1}). We assume an indoor ozone mixing ratio of 20 ppb ($40 \mu\text{g m}^{-3}$) (18), which is anticipated to occur near midday during the ozone season in a typical indoor setting. Since our deposition velocity values were obtained from a field emission cell at a high air exchange rate, we chose to use a more conservative value, 1.44 m h^{-1} , estimated for carpet under average air velocity conditions (15). Values for A , V , and λ were taken from Table 1 and aldehyde yields were taken from individual experiments (see Figure 3 and Supporting Information, Table SII). As an example for home H1, the estimated SERs for nonanal and 2-nonenal from carpet are 17 and $3.4 \mu\text{g m}^{-2} \text{h}^{-1}$ respectively. The steady-state concentration increment due to secondary emissions of nonanal and 2-nonenal from carpet alone is estimated to be 16 and $3.1 \mu\text{g m}^{-3}$. The odor threshold for nonanal has been reported to be 13 (19) or $2 \mu\text{g m}^{-3}$ (20), and for 2-nonenal is reportedly $0.8 \mu\text{g m}^{-3}$ (19). Thus, even for moderate indoor ozone levels, the estimated concentration increments of nonanal and 2-nonenal, due to H1 carpet, exceed their odor thresholds. Further, we find that odor thresholds would be exceeded in home H2 for nonanal due to the kitchen floor, and 2-nonenal due to the living room carpet. We did not observe 2-nonenal in building air samples, but the nonanal concentrations were of the same order of magnitude as these estimates. Where formaldehyde yield was quantifiable, the estimated indoor concentration increment was less than $3 \mu\text{g m}^{-3}$.

Acknowledgments

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Note Added after ASAP Publication

There were errors in the first paragraph of the Chemical Analysis subsection and in Figure 7 in the version published ASAP on July 22, 2006; the corrected version was published ASAP July 31, 2006.

Supporting Information Available

Field emission cell description and figure, and tables of data. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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