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Prescribed Burns and Wildfires in Colorado: Impacts of Mitigation Measures on Indoor Air Particulate Matter

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ABSTRACT

Wildfires and prescribed burns are receiving increasing attention as sources of fine particulate matter ($PM_{2.5}$). The goal of this research project was to understand the impact of mitigation strategies for residences impacted by scheduled prescribed burns and wildfires. Pairs of residences were solicited to have $PM_{2.5}$ concentrations monitored inside and outside of their houses during four fires. The effect of using air cleaners on indoor $PM_{2.5}$ was investigated, as well as the effect of keeping windows closed. Appropriately sized air cleaners were provided to one of each pair of residences; occupants of all of the residences were asked to keep windows shut and minimize opening of exterior doors. Additionally, residents were asked to record all of the activities that may be a source of particulate matter, such as cooking and cleaning. Measurements were made during one prescribed burn and three wildfires during the 2002 fire season. Outdoor 24-hr average $PM_{2.5}$ concentrations ranging from 6 to 38 $\mu g/m^3$ were measured during the fires, compared with levels of 2–5 $\mu g/m^3$ during background measurements when no fires were burning. During the fires, $PM_{2.5}$ was <3 $\mu g/m^3$ inside all of the houses with air cleaners installed. This corresponds with a decrease of 63–88% in homes with the air cleaners operating when compared with homes without air cleaners. In the homes without the air cleaners, measured indoor concentrations were 58–100% of the concentrations measured outdoors.

IMPLICATIONS

Wildfires and prescribed burns located tens of kilometers away from residences can increase both outdoor and indoor $PM_{2.5}$ concentrations. In this study, pairs of residences were solicited to have $PM_{2.5}$ concentrations monitored inside and outside of their houses during four fires. The effect of using air cleaners on indoor $PM_{2.5}$ was investigated, as well as the effect of keeping windows closed. Residents, especially those with asthma or other preexisting respiratory problems, should be advised to consider operating air cleaners when fires are burning in the vicinity, rather than just to stay indoors with doors and windows closed.

INTRODUCTION

Smoke produced from wildfires, controlled burns, and agricultural burns is of increasing concern as a potentially significant source of human exposure to airborne particulate matter (PM). During the 2001, 2002, and 2003 seasons, 3,600,000, 6,900,000, and 4,900,000 acres, respectively, burned nationwide in the U.S. in wildland fires.[1] In 2000, forest fires in Montana and Idaho consumed >2,000,000 acres and for an entire month produced fine PM ($PM_{2.5}$) concentrations in Missoula, MT, >15 $\mu g/m^3$.[2] In 2002, the Hayman fire in Colorado produced a peak 24-hr average $PM_{2.5}$ concentration of 46 $\mu g/m^3$ in downtown Denver.[3] Although below the current national ambient air quality standard for $PM_{2.5}$, exposure to concentrations at this level, nevertheless, threatens human health.[4]

In addition to wildfires, prescribed burns adjacent to populated areas may potentially expose residents to high levels of smoke.[5] Land managers are increasingly turning to prescribed burns to reduce fuel loadings and to restore ecosystems where fire played a natural role. The annual target for prescribed burns was set to be >3,000,000 acres by the year 2003,[5] compared with <1,000,000 acres burned in 2000 (the latest year for which data are available).[6]

Wildfire emissions are composed of a complex mixture of products of incomplete biomass combustion, including polynuclear aromatic hydrocarbons, carbon monoxide (CO), aldehydes, organic acids, and other semivolatile and volatile organic compounds.[7] Some of these compounds are significant over local scales because of toxicity to humans and reduced visibility. Others, like methane and carbon dioxide (CO_2), have a global impact as greenhouse gases. PM is of special interest because of the large quantity produced during biomass combustion (~4–20 g of $PM_{2.5}$ per kilogram of fuel depending on combustion efficiency)[8] and because of its impact on human health. The organic carbon fraction of PM is known to contain numerous carcinogenic compounds.[2] Particles are also known to carry adsorbed and condensed toxic gases and, possibly, free radicals.[7] Increased PM levels from biomass fires have been associated with increases in outpatient hospital visits, respiratory infection, asthma, and rhinitis.[9–11]

Both ground-based and airborne sampling of emissions released from wildland fires shows that fine particles predominate over coarse particles. In airborne measurements of particles from logging slash burns in the Western United States, Radke et al.[12] found that the peak in the number concentration distribution occurred at a diameter of 0.15 μm. The mass concentration was found to have bimodal peaks at diameters of 0.5 μm and $>$43 μm. Ward and Smith[2] found that smoldering combustion releases several times more fine particles than flaming combustion. Fine particles with a mode in the mass distribution at 0.3 μm account for nearly 100% of the mass of PM during smoldering combustion.[2] Flaming combustion produces from 80 to 95% fine particles.[2,7]

To mitigate exposures to smoke during wildfires and prescribed burns, public health officials often recommend that residents in the area remain indoors, with doors and windows shut. However, the effectiveness of remaining indoors to reduce PM exposure from outdoor sources depends on the characteristics of the building. The impact of outdoor particles on indoor levels is influenced by the rate of air infiltration. The annual average air-exchange rate (AER) for homes in Colorado is 0.55 air changes per hour.[13] This typical home would have a steady-state indoor particle concentration of 73% of the outdoor concentration, assuming a penetration factor (PF) of 1 and a particle deposition rate of 0.2 hr^{-1}.

Portable air cleaners are compact, stand-alone appliances designed to lower particulate levels in an enclosed space. Portable air cleaners are effective at reducing indoor particle levels, provided the specific cleaner is adequately sized to the indoor environment in which it is placed.[14] Many air cleaners operate by drawing the particle-laden air across a porous filter medium or electrically charged plates. Air cleaners are classified by their clean air delivery rate (CADR), which describes the volume of air that the specific cleaner can filter. By matching the CADR of a device to the specific space in which it is placed, effective air cleaning can be achieved.

The approach used in this study was to measure indoor and outdoor $PM_{2.5}$ concentrations in and near impacted residences during scheduled prescribed burns and wildfires of opportunity and to assess the performance of air cleaners for reducing exposure during such episodes. Over the duration of the study, one prescribed burn and three wildfires were monitored. During each fire, $PM_{2.5}$ concentrations were measured indoors and outdoors at two affected residences. In both homes, the residents were instructed to keep all of the windows and doors closed. One of the homes was designated as an intervention site. Portable air cleaners were provided, and the residents were instructed to operate the air cleaners continuously during the fire. Measurements were made for simultaneous 24-hr periods at each of the two houses for a given fire location. These measurements were then compared to determine the effectiveness of the air cleaners and the effectiveness of keeping the windows closed in reducing the indoor concentration of $PM_{2.5}$ from fire smoke.

MATERIALS AND METHODS

Fire Identification and Participant Recruitment

Prescribed burns and wildfires were identified for this study through contact with the U.S. Forest Service (USFS) and local wildland fire agencies and through monitoring the local news several times a day during periods of high-fire danger. During the course of this study, $PM_{2.5}$ levels at nearby residences were monitored during the following four fires: (1) the Polhemus prescribed burn in October 2001, which consumed ~8000 acres located 5 km east of Deckers, CO; (2) the Snaking fire in April 2002, which consumed ~2600 acres located ~6 km west of Bailey, CO; (3) the Schoonover fire in May 2002, which consumed ~3400 acres located 5 km south of Deckers, CO; and (4) the Hayman fire in June 2002, which, ultimately, consumed ~138,000 acres near Deckers, CO.

Once a fire was burning, the local USFS office was contacted for an exact location of the fire. The location of the smoke-impacted communities was then determined by locating the fire on a U.S. Geographical Survey topographical map. With the topographical layout of the land known, the smoke movement could be approximated. The most reliable smoke movement is nighttime drainage, when the air surrounding the smoke cools because of nighttime radiation cooling and drains into stream and river valleys. This phenomenon occurred during all three of the wildfires studied in this project. Towns along this smoke drainage route were targeted as potential locations to find volunteers. Distances of 10–30 km from the fire were targeted to reduce the threat that evacuations would interrupt the study.

Several methods were used to find volunteers. The first approach was visiting the local volunteer fire department. The fire chief was informed of the project and asked to contact any firefighters he thought would be willing to participate. All of the firefighters contacted were willing to volunteer for the study. This method was used for the Polhemus controlled burn and Snaking wildfire. The only potential problem with this method was that the firefighters were away fighting the fire and not home during the monitoring periods. Therefore, arrangements with neighbors had to be made to provide entry into their homes. During the Schoonover wildfire, residents of Roxborough Park who called the Colorado Department of Public Health and Environment (CDPHE) to complain about smoke were recruited as volunteers. An additional recruitment method was direct contact with acquaintances impacted by the Hayman wildfire.

All of the homes recruited for the study were single homes of similar age, to facilitate comparison. Residents were also confirmed to be nonsmokers, and wood-burning stoves were not used. Residents were asked to keep all of their windows and doors shut.

Questionnaire and Activity Diary

A questionnaire was administered to each resident participating in the study documenting the characteristics of the home that might affect PM levels indoors. Important details include house age; number and type of windows; type of heating, ventilation, and air conditioning system; and presence of any indoor PM source.

In addition to the questionnaires, the residents were asked to fill out a diary of activities during the monitoring period. These were designed to identify any indoor PM sources, such as cooking or cleaning, which may have been present during the monitoring period. The diary was also used to track whether any windows or doors were opened during the sampling period. Several participants did not complete diaries, because they were away from the house for the majority of the monitoring period.

Air Cleaners

The air cleaners that were used during this study are Friedrich C90 electrostatic precipitating (ESP) cleaners (Friedrich Air Conditioning Company). These units weigh 12 kg and are 48 × 38 × 56 cm. In an ESP cleaner, a high-voltage wire charges particles drawn into the unit. These particles are then attracted to a precipitating cell carrying the opposite electrical charge and thereby removed from the airstream.

A useful parameter for characterizing effectiveness of an air cleaner is the CADR, which is equal to the single-pass efficiency times the airflow rate through the device. The CADR for the Friedrich C90 is reported to be 390–510 m^3/hr for smoke and dust removal.[15] Three tests were performed at the University of Colorado Indoor Air Quality Laboratory[16] to estimate the CADR of the air cleaners. An average CADR of 404 ± 29.4 m^3/hr was measured. Using a well-mixed reactor model and assuming an AER of 1 hr^{-1} and a particle loss rate of 0.2 hr^{-1}, a steady-state reduction in particle concentrations of 80% can be achieved in a volume of 78–90 m^3.[17] Thus, for a house that has a volume of 340 m^3 (1500 ft^2 with an 8-ft ceiling), at least three units would need to be installed throughout the house.

Ozone can be a concern when using ESP air cleaners. Before the use of the air cleaners in this study, measurements were made of ozone levels at the inlet and outlet of the air cleaner while it was operating with an UV photometric ozone analyzer (Thermo Environmental Instruments, Inc., Model 49). A new, unused air cleaner measured 2 ppb at both the inlet and outlet, and an air cleaner that had been operated for 6 weeks continuously showed a maximum production of four ppb of ozone.

Environmental Monitoring

Twenty-four hour average $PM_{2.5}$ mass concentrations were measured using single-stage impactors (Harvard Impactors, Air Diagnostics and Engineering Inc.). Two-micron pore-size Teflon 37-mm polytetrafluoroethylene (PTFE) membrane filters with a support ring (# R2PJ037, Gelman Sciences) were preweighed by CDPHE in their $PM_{2.5}$ gravimetric analysis facilities and loaded into impactor filter cassettes. Loaded cassettes were picked up from CDPHE and transported to and stored in a freezer at −30 °C at the University of Colorado until the monitoring event. On the day of sampling, the filter cassettes were loaded into a cooler with ice substitutes and a minimum/maximum thermometer and transported to the monitoring site. Once the sampling locations were identified (main living area and back porch), the impactors and pumps were set up, and cassettes were then loaded into the impactor. Two samplers to provide duplicate measurements were placed both indoors and outdoors at the study site. Samplers were placed on a table at similar heights above the floor, at ~0.8 m. The sample pumps were calibrated to 20 L/min before and after the sampling event (Dry Cal, DC-Lite). Sampling was initiated in the afternoon or evening (between 1:00 p.m. and 9:00 p.m.) and continued for 24 hr. After the sample period had ended, a return trip to the site was made to pick up the equipment. Filter cassettes were then unloaded into the cooler and transported back to the University of Colorado. The filters were then stored at a temperature of −30 °C until transport to CDPHE (~2 weeks) for postgravimetric analysis

An optical particle counter (OPC; MetOne, 237B) was used during the first fire event (Pohlemus prescribed burn) to count particles as a function of time in six size bins: 0.3–0.5, 0.5–0.7, 0.7–1, 1–2, 2–5, and >5 μm. The instrument was located inside the study home, near to a window. A sample-line switching valve controlled by an interval timer was operated that would allow the unit to sample indoors and also outdoors using a sample line placed out a window. The outside sample line was routed through a window opened just enough to pass the sample tube through. This apparatus was tested in the field using two additional Climet optical particle counters (Climet, CI-4102A) measuring the indoor and outdoor concentrations. This test showed that there was some contamination between the indoor and outdoor samples. The level of contamination was <10%, and the two indoor measurements track each other quite well with some positive bias to the MetOne. The outdoor MetOne showed some contamination when the indoor concentration was elevated. There may also have been some unknown error introduced by a window being cracked for the sample line. Because of these errors, four Climet counters, on loan from the U.S. Environmental Protection Agency (EPA) Radiation and Indoor Environments National Laboratory, were used for the rest of the study. These units count particles in two size bins: >0.5 μm and >5 μm. Two Climet counters were operated indoors and two outdoors during all of the other sampling campaigns. When compared side by side, the results from the Climet counters agreed to within 10% of each other.

The indoor monitoring equipment was set up neatly, out of the way, in a central location, such as a living area. If there was a table in the area, it was used as a platform to elevate the samplers into the breathing zone. If there was no table available, a portable 1.5-m stand was used. The outdoor location needed to be protected from the rain, so a front or rear porch was an ideal location. Again, the samplers were placed on a ledge or table for elevation into the breathing zone.

AERs

A tracer gas decay method was used to measure the AER of the homes studied. Carbon dioxide (CO_2) was used as the tracer, because it is nontoxic to humans. CO_2 was continually released into the home from a regulated gas cylinder for ~15–20 min, until the inside concentration reached 5000 ppm. During this period, the tank was placed as far as possible from the monitor to allow the CO_2 to mix within the indoor air before reaching the monitor. Once the concentration reached 5000 ppm, the gas cylinder was shut off, and the homeowners were instructed to keep the doors and windows shut. The CO_2 concentration, as a function of time, was measured over the course of the CO_2 build-up and decay using diffusion CO_2 monitors (Langan, model L76). CO_2 data were logged every minute for 24 hr. The average AER could be estimated using a mass balance model from the decay data.

Meteorological Data

Wind speed and wind direction data from the CDPHE Welch monitoring station located in Denver County near Sheridan were used to help explain the movement of the smoke during the sampling periods for the Pohlemus burn and the Schoonover and Hayman fires.

Indoor Air Quality Model

An analytical indoor air quality model was used to predict indoor PM number concentrations as a function of time in the study homes. The model assumes that a house can be represented as a single well-mixed reactor[14,18] and that indoor air exchanges via airflow with the outside air. The airflow rate into the house (Q_O [m^3/hr]) is assumed constant over the simulation period, the system is assumed to be isothermal, and the indoor air pressure is assumed to be constant for the entire house. A continuous but time-varying source of particles is introduced beginning at time $t_{0,}$ corresponding to the particle number concentration that is measured outside during a fire (C_O[t] [particles/m^3]).

A fraction of the outdoor particles penetrate the building shell. The PF represents the ability of the building to remove particles from the air moving outside to inside.[19] For wildfire smoke with a mean mass diameter of 0.3 μm, the PF is estimated to be 1.[20]

Once the particles enter the building, they are assumed to be instantaneously and uniformly mixed within the house and to remain well mixed. In this model, the particles are assumed to be conservative; that is, they do not coagulate, evaporate, or grow by condensation within the space.

Particles are removed from the indoor air by surface deposition with rate constant k (hr^{-1}), by airflow out of the house (Q_O [m^3/hr]), and by filtration with an air cleaner that has a single-pass PM removal efficiency of η and airflow rate Q_f (m^3/hr).[14] It is assumed that there are no particles generated in the indoor air. The deposition rate constant 0.2 hr^{-1} was used throughout this study based on measurements in a furnished room for particles that are 0.5 μm in diameter.[21]

Given these conditions, the indoor particle concentration as a function of time can be described by a differential equation derived from the principle of mass conservation as follows:

$$\frac{dC(t)}{dt} = \frac{1}{V}\left(PFQ_O C_O(t) - [kV + \eta Q_f + Q_O]C(t)\right) \quad (1)$$

To model a residence in which an air cleaner is not operated, the term for particle removal by filtration is eliminated. For a short time interval, Δt, the solution to eq 1 is as follows:

$$C(t + \Delta t) = C(t) + \Delta t \lambda \; 0.5[C_O(t) + C_O(t + \Delta t)] - \Delta t(k + \eta \; Q_f/V + \lambda)C(t) \quad (2)$$

The model was applied with the assumptions that the PF is 1 and k is 0.2 hr^{-1}. The AER is $\lambda = Q_O/V$, and Δt is the time step between measurements. C_O(t) is defined as the average outdoor concentration between time steps. These equations are solved subject to the following initial condition: $t = t_O, C(t) = C_i$, where the initial indoor concentration (C_i) is the background indoor air concentration.

Effectiveness of Keeping Windows Closed and Operating Air Cleaners

The objectives of this project included investigating how effective it is to reduce PM exposure during a fire by staying inside with the windows closed and determining how effective air cleaners are at reducing indoor $PM_{2.5}$ from smoke. The following parameters are used to quantify the impact of keeping windows closed or operating air cleaners and are calculated using $PM_{2.5}$ 24-hr time-averaged mass concentrations measured with impactors.

The infiltration factor is the equilibrium fraction of outdoor particles that penetrate inside and remain suspended.[22,23] The infiltration factor is a function of the AER, the deposition rate, and the penetration factor.[24] If indoor particle generation and resuspension are negligible compared with outdoor sources, the infiltration factor is equivalent to the indoor-outdoor (I/O) ratio:

$$\text{Infiltration Factor} = \frac{PF(Q_O/V)}{(Q_O/V) + k} = \frac{PM_{2.5}\ \text{Inside}}{PM_{2.5}\ \text{Outside}} \tag{3}$$

Assuming outdoor particle generation dominates during fires, the I/O ratio was used for homes without an air cleaner as a measure of the effectiveness of keeping windows closed for reducing indoor $PM_{2.5}$ concentrations. The assumption that indoor sources were negligible generally held, with one exception as discussed below.

The effectiveness of operating an air cleaner for reducing indoor $PM_{2.5}$ concentrations in house A compared with house B, which does not have an air cleaner, is estimated using eq 4:

$$\left(\begin{matrix}\text{Percent } PM_{2.5}\text{reduction}\\ \text{due to air cleaner}\end{matrix}\right)_{\text{House A}} = \left[1 - \frac{\left(\dfrac{PM_{2.5}\ \textit{Inside w air cleaner}}{PM_{2.5}\ \textit{Outside}}\right)_{\text{House A}}}{\left(\dfrac{PM_{2.5}\ \textit{Inside w/o air cleaner}}{PM_{2.5}\ \textit{Outside}}\right)_{\text{House B}}}\right] \times 100\% \tag{4}$$

The higher the effectiveness value, the better the control strategy for reducing exposure to PM. These evaluations assume that the air infiltration rates and PFs are similar between houses and that the main source of particles inside the home comes from outdoors (i.e., no particles generated indoors).

RESULTS AND DISCUSSION

Polhemus Prescribed Burn

The two homes that were selected for study were located in an area that had reported smoke from previous prescribed burns. Two volunteers were located by contacting the local fire chief. House characteristics are found in Table 1. The study results for this fire are found in Table 2. House Polhemus (P)2 was supplied with two air cleaners, whereas house P1 had none. Data for house P1 are complete. Data for house P2, however, are not complete, because some equipment malfunctioned. The timer for the OPC failed to come on, and one of the two indoor Harvard impactors did not come on.

Table 2 shows the 24-hr time-weighted average $PM_{2.5}$ mass concentrations measured during and after the Pohlemus prescribed burn. Outdoor $PM_{2.5}$ concentrations were comparable at the two study houses both during the fire and when background concentrations were later measured. $PM_{2.5}$ was 13 times higher outside house P1 and 11 times higher outside house P2 during the burn compared with the background concentrations measured outside the homes. Indoor $PM_{2.5}$ concentrations differed between house P1 and house P2 both during the burn and when background was measured. $PM_{2.5}$ was 6.4 times higher inside house P1 during the burn compared with inside when background was measured. For house P2 (with air cleaners), however, the indoor $PM_{2.5}$ concentration during the fire was 3.5 times lower compared with the indoor $PM_{2.5}$ concentration when background was measured.

Figure 1 shows the particle number concentration as a function of time in house P1 as measured by the OPC for a 16-hr period starting at 5:00 p.m. The indoor and outdoor concentrations peaked at ~12:30 a.m. on October 21, 2001. At 4:00 a.m., the outside concentration dropped abruptly. This abrupt drop occurred just after a 2-hr period of increased winds (15–18 km/hr) and a 90° change in wind direction from northwesterly to southwesterly. During this period of reduced outdoor concentration, the AER of the house could be estimated by evaluating the indoor particle concentration decay. This evaluation revealed an AER of 0.23 hr^{-1}. This value is in close agreement with the value measured by the CO_2 tracer gas technique (Table 1).

Indoor PM concentrations predicted by the indoor air quality model are also displayed in Figure 1. The modeled concentrations follow general indoor trends but do not capture the transient peaks, for example, the peak at 12:00 a.m.

Table 1. Characteristics of the houses monitored during the Polhemus prescribed burn, Snaking, Schnoover, and Hayman wildfires.

Characteristic	House P1	House P2	House Sn1	House Sn2	House Sc1	House Sc2	House H1	House H2
Location relative to fire	24 km north	27 km north	11 km east	11 km east	24 km north	24 km north	47 km northeast	47 km northeast
House volume	815 m^3	407 m^3	424 m^3	453 m^3	1415 m^3	1130 m^3	510 m^3	396 m^3
Age of house	7 yr	5 yr	~30 yr	3 yr	6 yr	5 yr	39 yr	39 yr
Building material								
Floor	Wood, carpet (50%)	Wood, carpet (90%)	Wood	Wood (90%), carpet	Wood, carpet (50%)	Wood, carpet (5%)	Wood	Wood
Walls	Drywall, vinyl siding	Drywall, vinyl siding	Drywall	Drywall	Drywall, stucco siding	Drywall, stucco siding	Sheetrock	Sheetrock
Levels	3 (basement)	3 (basement)	2	2 (basement)	2 (basement)	2 (basement)	3 split level	2 (basement)
Heating system	Forced air	Forced air	Forced air	Forced air	Forced air	Radiant floor	Forced air	Forced air
% Time on	~35%	~40%	50%	10%	0%	0%	10–50%	10–50%
Humidifier	Yes	No	No	No	Yes	No	No	No
HVAC air filter	Standard furnace	High-efficiency furnace	Standard HVAC	Standard HVAC	Standard furnace	None	Standard furnace	Standard furnace
Wood burning stove	No	No	No	Yes	No	No	No	No
Windows								
Number	27	17	13	7	37	28	10	21
% Time opened	0%	0%	0%	10%	5%	0%	0%	0%
Number air cleaners operated during fire		2	2 operated during fire on 4/26–27	2 operated during fire on 4/25–26	3		3	
AER (hr^{-1})	0.21	0.19	0.71	0.48	0.17	0.16	0.15	0.1

Note: P = Polhemus; Sn = Snaking; Sc = Schnoover; and H = Hayman.

Snaking Wildfire

The two homes selected for the study are located in the town of Pine, where smoke from the wildfire had been observed on the previous day. Pine (2050-m elevation) is located directly downhill from the fire area (2450-m elevation). Two volunteers were located by contacting the local fire chief. House characteristics are found in Table 1. Smoke was present in the area of Pine for multiple days, thus, measurements were made for 2 days. This provided the opportunity to investigate the effects of air cleaners in both study homes. During the first 24-hr period (April 25 to April 26, 2002) House Snaking (Sn)2 was provided with two air cleaners; the air cleaners were moved to house Sn1 for the second 24-hr period. Note that the AER for the study homes were different by ~30%: Sn1 had an AER of 0.71 hr^{-1} and Sn2 had an AER of 0.48 hr^{-1}.

Table 2 shows the 24-hr time-weighted average $PM_{2.5}$ mass concentrations measured during and after the fire on both monitoring days. Outdoor $PM_{2.5}$ concentrations are comparable at the two study houses both during and after the fire. For the period of April 25 to April 26, $PM_{2.5}$ was 2.5 times higher outside house Sn1 and 2.4 times higher outside of house Sn2 during the fire when compared with the later background measurements. Indoor $PM_{2.5}$ concentrations differed between the two houses during the fire. $PM_{2.5}$ was 2.1 times higher inside house Sn1 during the fire compared with inside when the background was measured. For house Sn2 (with air cleaners), however, the indoor $PM_{2.5}$ concentration during the fire was 2.2 times lower compared with the indoor $PM_{2.5}$ concentration when the background was measured. Also, during the fire, the indoor concentration inside house Sn1 was ~10% higher compared with the outdoor concentration. This is possibly because of a cooking event that evening at ~6:00 p.m. (see Figure 2), although no cooking event was recorded in the activity diary.

During the second day of monitoring (April 26 to April 27, 2002) the outdoor 24-hr average $PM_{2.5}$ concentrations were two times higher outside house Sn1 and 1.4 times higher outside of House Sn2 during the fire when compared with the later outside background measurements. Inside house Sn1 (with air cleaners), the $PM_{2.5}$ concentration was two times lower during the fire compared with inside when the background was measured. Inside house Sn2, the $PM_{2.5}$ concentration was 1.1 times higher during the fire compared with inside when the background was measured. The EPA Aerometric Information Retrieval System did not have a monitoring site near

Table 2. PM$_{2.5}$ 24-hr time-weighted average mass concentrations (μg/m^3; average and difference of duplicate samples) measured during the Polhemus prescribed burn, Snaking, Schnoover, and Hayman wildfires.

House	Inside During Fire	Outside During Fire	Inside Background	Outside Background
P prescribed burn fire date: 10/20/01–10/21/01, background date: 11/19/01–11/20/01				
House P1	21.8 (2.6)	37.5 (2.1)	3.42 (0.27)	2.85 (1.86)
House P2[a]	2.00[b]	21.7 (0.1)	7.00 (0.35)	1.99 (0.65)
Sn wildfire fire date: 4/25/02–4/26/02, background date: 7/25/02–7/26/02				
House Sn1	10.9 (0.51)	9.50 (0.50)	5.24 (0.21)	3.78 (0.32)
House Sn2[a]	2.06 (0.18)	9.24 (0.07)	4.52 (0.27)	3.91 (0.08)
Sn wildfire fire date: 4/26/02–4/27/02, background date: 7/25/02–7/26/02				
House Sn1[a]	2.61 (0.12)	7.52 (0.37)[c]	5.24 (0.21)	3.78 (0.32)
House Sn2	5.16 (0.37)	5.54 (0.61)	4.52 (0.27)	3.91 (0.08)
Sc wildfire fire date: 5/22/02–5/23/02, background date: 5/31/02–6/01/02				
House Sc1[a]	1.43 (0.00)	20.7 (1.1)	4.95 (0.31)	5.08 (0.37)
House Sc2	11.4 (0.2)	19.6 (2.9)	4.86 (0.80)	4.88 (0.10)
H wildfire fire date: 6/18/02–6/19/02, background date: 7/16/02–7/17/02				
House H1[a]	3.02 (0.49)	32.7 (1.5)	7.49 (2.22)	4.96 (1.14)
House H2	24.5 (0.07)	32.9 (2.4)	5.01 (0.56)	4.56 (0.11)

Note: P = Polhemus; Sn = Snaking; Sc = Schnoover; and H = Hayman; [a]Air cleaners installed; [b]Pump failure, only one sample obtained; [c]Power failure caused samplers to run for 12 hr only; [d]Only one sample available for analysis.

this fire, and, therefore, meteorological information is not presented.

The OPC measurements made during the fire inside and outside house Sn1 for the two sample periods are shown in Figures 2 and 3, respectively. Figure 2 shows that smoke present during the April 25 to April 26 sampling period peaked for a short duration (<1 hr). This peak was followed by 9 hr of increased outdoor air concentration. The indoor concentration increases quickly once there is smoke present outside. There is a small peak in indoor concentrations around 6:00 p.m., as mentioned above, before the smoke penetrates the home, most likely because of cooking. Figure 3 shows that the smoke monitored during the April 25 to April 26 period does not exhibit a pronounced peak like on the previous day. The outdoor concentration is roughly stable for 14 hr. The indoor concentration during this period averages

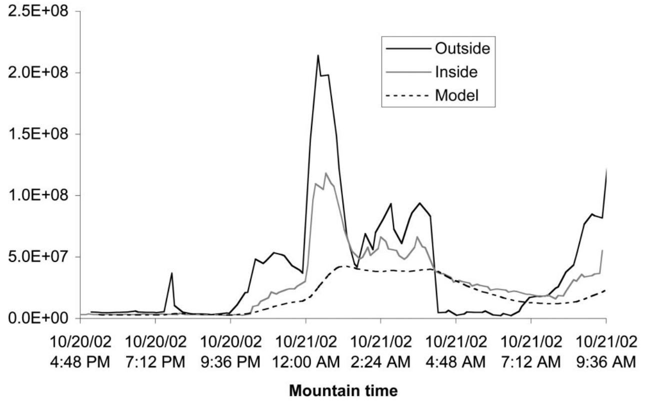

Figure 1. House P1 inside and outside measured particle concentrations during the Polhemus prescribed burn. Also shown are the modeled indoor air concentrations. Units are number/m^3 of particles between 0.5 and 5 μm.

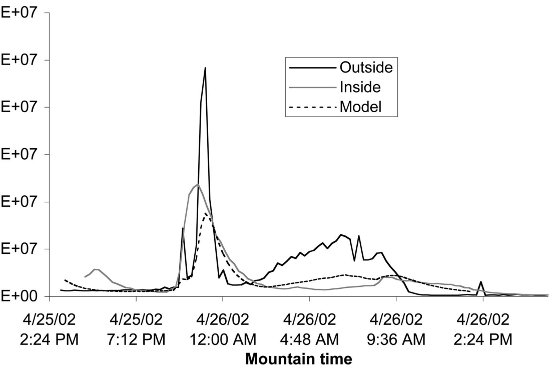

Figure 2. House Sn1 inside and outside measured particle concentrations during the Snaking first monitoring period of April 25 to April 26, 2002. Also shown are modeled indoor air concentrations. Units are number/m^3 of particles between 0.5 and 5 μm.

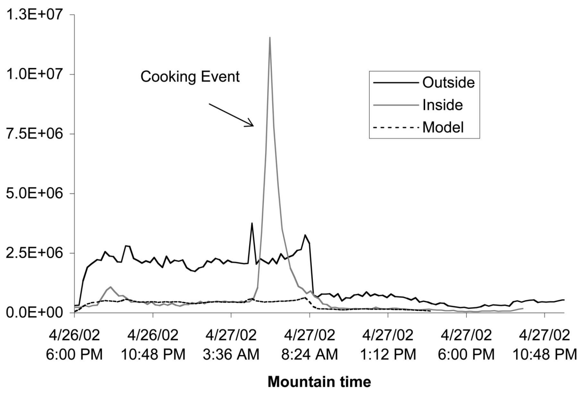

Figure 3. House Sn1 inside and outside measured particle concentrations during the Snaking Fire second monitoring day, April 26 to April 27, 2002. On this day, two air cleaners were installed in the house. Also shown are modeled indoor air concentrations. Units are number/m^3 of particles between 0.5 and 5 μm. The indoor peak at 5:00 a.m. was caused by a cooking event, as documented in the activity diaries of occupants.

an order of magnitude lower until a cooking event at 5:45 a.m. raises the indoor concentration. This event was documented on the diary of activities for this day. In this case, the assumption that the infiltration factor is approximated by the I/O ratio does not hold, because there is a significant indoor source (eq 3).

Figures 2 and 3 also show predicted indoor air concentrations. The model predicts well the indoor air particulate profile on April 25 to April 26 (Figure 2). On April 26 to April 27, however, the model does not predict the large peak at 5:45 a.m. (Figure 3), because the cooking source is not accounted for in the model.

Schoonover Wildfire

Initially, volunteers were sought in Deckers, in the South Platte River valley. This was the closest community to the fire, and the smoke was sure to drain down the valley that night. Several residents were contacted through door-to-door solicitation but were unwilling to participate, because fire evacuations were highly likely (evacuation occurred on May 22). Roxbourgh Park was the next location located downstream on the Platte River. This area had smoke impact during the Polhemus prescribed burn, so it was assumed that there would, again, be impact in this area. One volunteer was found through CDPHE, and the second volunteer was a neighbor of the first. The house characteristics are shown in Table 1.

Table 2 presents the 24-hr time-weighted average $PM_{2.5}$ mass concentrations measured during and after the fire. Outdoor $PM_{2.5}$ concentrations are comparable at the two study houses both during and after the fire. This is expected, because the two houses are located ~100 m apart. $PM_{2.5}$ is 4.1 times higher outside house Schnoover (Sc)1 and four times higher outside of house Sc2 during the fire when compared with the background. Indoor $PM_{2.5}$ concentrations differed between the two houses as expected. House Sc2 had indoor $PM_{2.5}$ measurements 2.4 times higher during the fire than during the background measurement, whereas house Sc1 (with air cleaners) had indoor $PM_{2.5}$ concentration 3.5 times lower during the fire than during background.

The OPC measurements for house Sc1 are shown in Figure 4. The peak outdoor concentration occurred at ~6 a.m. The smoke was present for 3 hr. These results show a much-reduced indoor concentration in both maximum and duration when compared with outdoors. Also shown in Figure 4 are the model predictions for the indoor air concentrations. The model overpredicts the concentration but follows the trend reasonably well.

Wind speed and wind direction data were obtained from the CDPHE Welch monitoring station, which was located 8-km south of the monitoring sites. At 2:00 a.m. on May 23, 2002, the wind was coming directly from the south at 6.4 km/hr. The wind shifted directions to the east starting at 9:00 a.m. and increased in speed to >11 km/hr. This shift in direction and speed rapidly cleared the monitoring area of smoke (Figure 4).

Hayman Wildfire

The Hayman wildfire eventually became the largest in Colorado recorded history. By the time it was contained, it had consumed 137,760 acres along with 133 residences, one commercial building, and 466 outbuildings.[25] The smoke plume was visible for >1600 km and created its own weather patterns. The smoke produced by this fire heavily impacted the Denver metro area on June 9, 2002. The first sampling trip was conducted the next day, but the air was much less polluted, because the energy released by the fire was pushing the plume up above and

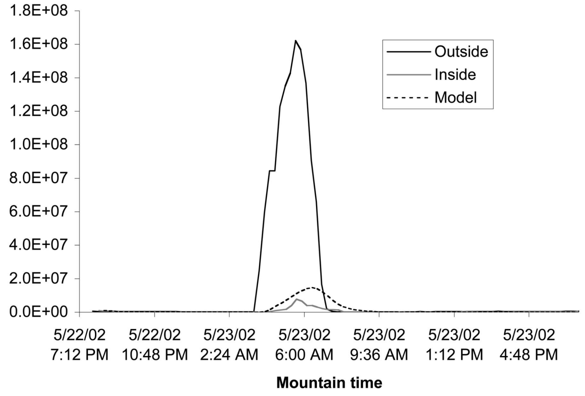

Figure 4. House Sc1 inside and outside measured particle concentrations during the Schoonover wildfire. Three air cleaners were installed during monitoring. Also shown are model predictions of indoor air concentrations. Units are number/m^3 of particles between 0.5 and 5 μm.

past the city. This phenomenon reduced the smoke impact, thus, this trip yielded no results. The second sampling session was conducted on June 18, 2002. This sampling period was chosen because of the presence of smoke during the previous day. The weather forecast for June 18, 2002, called for similar conditions as on June 17; therefore, there was a good chance for repeated smoke impacts. Volunteers for this monitoring period were found through CDPHE. Both homes had air conditioning in use during the fire, so they were ideal for the study. The house characteristics are found in Table 1.

Table 2 details the 24-hr time-weighted average $PM_{2.5}$ mass concentrations measured during and after the fire. Outdoor $PM_{2.5}$ concentrations were comparable at the study houses both during and after the fire. $PM_{2.5}$ was 6.6 times higher outside house Hayman (H)1, and 7.2 times higher outside of house H2 during the fire when compared with the background measurement. The inside $PM_{2.5}$ differed between the two houses as expected during the fire. House H1 (with air cleaners) had an indoor $PM_{2.5}$ concentration that was 2.5 times lower during the fire than during the background measurements. House H2 had an indoor $PM_{2.5}$ concentration that was 4.9 times higher during the fire than during the background measurements.

The OPC measurements for house H2 are shown in Figure 5. The peak outdoor concentration occurred at ~9:00 a.m. The smoke was present for 3 hr. These results show that the indoor concentration remains elevated for almost 3 hr after the outdoor concentration drops. Also shown in Figure 5 are the model predictions for the indoor air concentrations. After the first peak in particle concentration, the model underpredicts the particle decay rate, most likely because the model AER was too low compared with the actual AER in the home.

Wind speed and wind direction data were obtained from the CDPHE Welch monitoring station, which was located 10 km east of the monitoring sites. At 2:00 a.m. on May 23, the wind was coming directly from the south at 7.7 km/hr. The wind shifted directions to the northeast abruptly at 10 a.m. and increased in speed to 15.5 km/hr. This shift in direction and speed rapidly cleared the monitoring area of smoke (Figure 5).

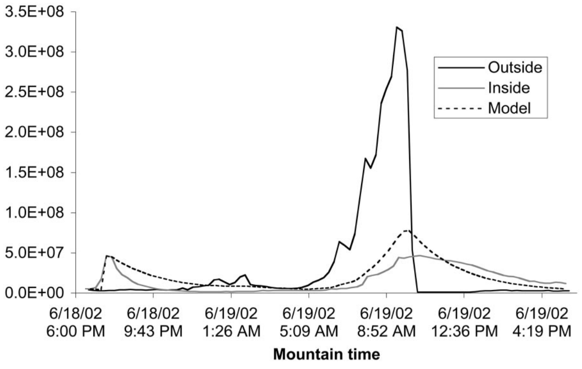

Figure 5. House H2 inside and outside measured particle concentrations during the Hayman fire. Also shown are the modeled indoor air concentrations. Units are number/m^3 of particles between 0.5 and 5 μm.

Effectiveness of Mitigation Measures

I/O ratios quantified for $PM_{2.5}$ are presented in Figure 6. These ratios provide an estimate of the effect of keeping windows closed and sheltering indoors. The $PM_{2.5}$ levels inside homes without air cleaners were 58–100% of outdoor levels, which agrees with previous estimates of I/O ratios in homes for periods in which there were no indoor sources or resuspension.[24] The highest I/O ratios are in the Snaking fire homes (Sn1 and Sn2), which had the highest AERs of all of the houses in the study (0.71 and 0.48 hr^{-1}). Also presented are model predictions using measured air exchange rates with PF at 1 and k at 0.2 hr^{-1}. The model predictions correlate reasonably well with the observations but are systematically low and differ from the measured values by 12–55%. The bias may be because of the fact that indoor sources were not considered in the model or that the deposition rate, k, was overestimated. These results indicate that during brief periods of smoke, a home with a low AER provides more protection than a house with a high AER.

The effectiveness of using air cleaners to mitigate smoke impacts is calculated using eq 4. The results are shown in Figure 7. The range in effectiveness of air cleaners across the five homes where they were used was 63–88%. Also presented are predictions using the indoor air quality model. The model was applied assuming steady state, with a CADR for the air cleaners of 404 m^3/hr and a k of 0.2 hr^{-1}. Measured AER values were used (Table 1).

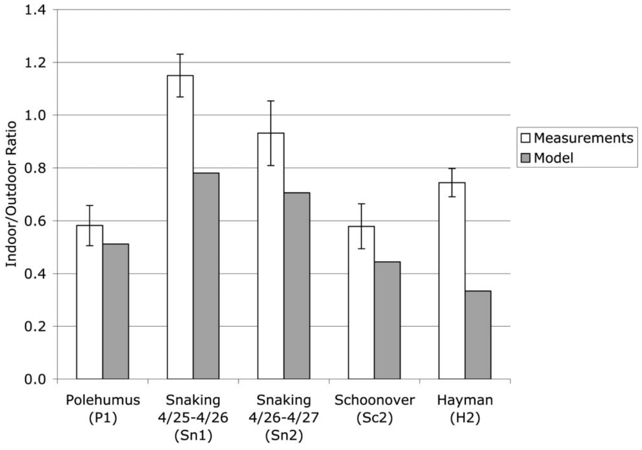

Figure 6. I/O ratios for houses with no air cleaners when fires were burning. Model values are based on the indoor air quality model used in this study (eq 1). Error bars represent propagation of range of duplicate measurements.

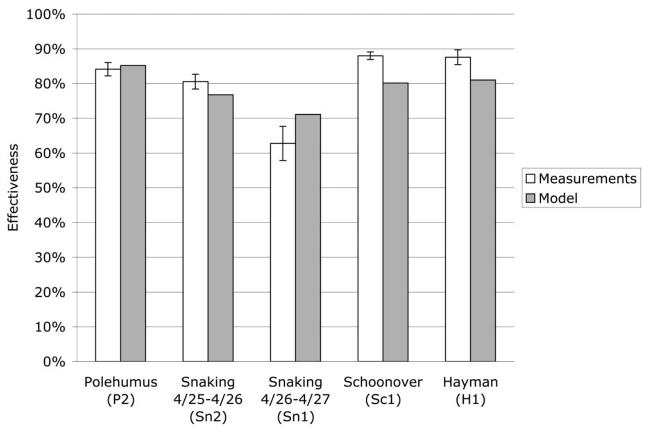

Figure 7. Effectiveness of operating air cleaners in homes when fires were burning. Model values are based on the indoor air quality model used in this study (eq 1). Error bars represent propagation of range of duplicate measurements.

Additionally, it was assumed that each air cleaner installed cleaned 90 m^3 of air, which was estimated previously as the volume of air in which the particle concentrations are reduced by 80%. Model predictions agreed well with the measured effectiveness. The largest difference was 13% for house Sn1.

For the Snaking fire, air-cleaner effectiveness was estimated by comparing houses Sn1 and Sn2 (Figure 7). Because the AER was higher in Sn1 compared with Sn2, the effectiveness in house Sn1 on April 26 to April 27 would be lower, and the effectiveness in house Sn2 on April 25 to April 26 would be higher compared with if these houses had more similar AERs. Specifically, this can be seen with additional analysis using data for house Sn1. Measurements on April 26 to April 27 when there were air cleaners operating are compared with measurements on April 25 to April 26 when there were no air cleaners, using eq 4. The effectiveness of air cleaners is 70%, which is higher than the 63% effectiveness shown in Figure 7. Similarly, for house Sn2, the effectiveness of using air cleaners is 76%, which is lower than the 81% shown in Figure 7.

This study tested only ESP-type air cleaners. Many other designs exist and have proven effective, such as filters containing fibrous filter media.[14] Other air cleaner designs would be just as effective as the air cleaners tested in this study, provided the CADR was appropriate for the indoor space in which it was applied.

CONCLUSIONS

Wildfires and prescribed burns located tens of kilometers away from residences can increase both outdoor and indoor $PM_{2.5}$ concentrations. In this study, outdoor 24-hr average $PM_{2.5}$ concentrations of 6–38 $\mu g/m^3$ were measured at homes that ranged from 11 to 47 km away from the fires. In comparison, 24-hr average concentrations of 2–5 $\mu g/m^3$ were measured at the same locations when no fires were burning. During the fires, inside the homes without air cleaners, 24-hr average $PM_{2.5}$ concentrations ranged from 5.2 to 21.8 $\mu g/m^3$ or from 58% to 100% of outdoor levels. With air cleaners operating, indoor 24-hr average $PM_{2.5}$ concentrations during the fires were ≤ 3 $\mu g/m^3$. By comparing pairs of similar, nearby homes located downwind from each fire, the effectiveness of air cleaners for $PM_{2.5}$ from smoke is estimated to be 63–88%.

Whereas limited size resolution precluded using the instantaneous OPC data obtained in this study to estimate mass concentrations, these particle counts were useful for determining the duration of smoke impacts and the dynamic response of the indoor concentrations. A well-mixed indoor air quality model with a PF of 1 and a k of 0.2 hr^{-1} performed reasonably well in capturing the dynamic response of indoor $PM_{2.5}$ levels to outdoor concentrations.

Expanding this study to include additional homes would be useful to investigate how various factors, such as home infiltration rates, affect protection from $PM_{2.5}$ generated outside. However, the results presented here suggest that agencies concerned with public health protection during prescribed burns and wildfires should consider changing their recommendations. Residents, especially those with asthma or other preexisting respiratory problems, should be advised to consider operating air cleaners when fires are burning in the vicinity, rather than just to stay indoors with doors and windows closed.

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REFERENCES

1. Wildland Fire Statistics; Available on National Interagency Fire Center Web site, http://www.nifc.gov/stats/wildlandfirestats.html (accessed August 24, 2005).
2. Ward, T.J.; Smith, G.C. *Air Sampling Study of the 2000 Montana Wildfire Season*; University of Montana, Department of Chemistry: Missoula, MT, 2001.
3. Air Quality Conditions Expected to Improve in Denver-Metropolitan Area Monday: Wildfire Smoke Continues to Impact Areas Throughout

Colorado; News Release; Colorado Department of Public Health and Environment: Denver, CO, June 10, 2002.

4. *Air Quality Criteria for Particulate Matter*, EPA 600/P-99/002aF-bF; U.S. Environmental Protection Agency: Washington, DC, 2004.
5. Background of the Role of Fire in North America, 1998; available on U.S. Environmental Protection Agency Web site http://www.westar.org/Docs/Fire/Append-a.PDF (accessed August 24, 2005).
6. Prescribed Fire Statistics; Available on National Interagency Fire Center Web site, http://www.nifc.gov/stats/prescribedfirestats.html (accessed August 24, 2005).
7. Ward, D.E. Smoke from Wildland Fires. In *Health Guidelines for Vegetation Fire Events*, *Background Papers*; Goh, K. -T.; Schwela, D.; Goldammer, J.G.; Simpson, O., Eds. World Health Organization: Lima, Peru, 1998; pp 75-85. Available at http://www.who.int/docstore/peh/Vegetation_fires/vegetationfirbackgrtoc.htm (accessed August 24, 2005).
8. Ward, D.E.; Hardy, C.C. Smoke Emissions from Wildland Fires; *Environ. Intl.* **1991**, *17,* 117-134.
9. Brauer, M. Health Impacts of Biomass Air Pollution. In *Health Guidelines for Vegetation Fire Events*, *Background Papers*; Goh, K. -T.; Schwela, D.; Goldammer, J.G.; Simpson, O., Eds. World Health Organization: Lima, Peru, 1998; pp 186-254.
10. Emmanuel, S.C. Impact to Lung Health of Haze From Forest Fires: The Singapore Experience; *Respirology* **2002**, *5,* 175-182.
11. Yudanarso, D. Smoke Episodes and Assessment of Health Impacts Related to Haze from Forest Fires: Indonesian Experience. In *Health Guidelines for Vegetation Fire Events*, *Background Papers*; Goh, K. -T.; Schwela, D.; Goldammer, J.G.; Simpson, O., Eds. World Health Organization: Lima, Peru, 1998; pp 313-333.
12. Radke, L.F.; Lyons, J.H.; Hobbs, P.V.; Hegg, D.A.; Sandberg, D.V. *Airborne Monitoring and Smoke Characterization of Prescribed Fires on Forest Lands in Western Washington and Oregon*; Government Reports Announcements Index, Issue 16, FSGTR PNW 251; U.S. Forest Service, Pacific Northwest Research Station: Portland, OR, 1990.
13. Murray, D.M.; Murmaster, D.E. Residential Air Exchange Rates in the United States: Empirical and Estimated Parametric Distributions by Season and Climatic Region; *Risk Analysis* **1995**, *15,* 459-465.
14. Miller-Leiden, S.; Lobascio, C.; Nazaroff, W.W.; Macher, J.M. Effectiveness of In-Room Air Filtration and Dilution Ventilation for Tuberculosis Infection Control; *J. Air & Waste Manage. Assoc.* **1996**, *46,* 869-882.
15. Household Air Cleaners; *Consumer Reports* **1992**, *October*, 657-662.
16. Xu, P.; Peccia, J.; Fabian, P.; Martyny, J.W.; Fennelly, K.; Hernandez, M.; Miller, S.L. Efficacy of Ultraviolet Germicidal Irradiation of Upper-Room Air in Inactivating Bacterial Spores and Mycobacteria in Full-Scale Studies; *Atmos. Environ.* **2003**, *37,* 405-419.
17. Nazaroff, W.W. Effectiveness of Air Cleaning Technologies. In *Proceedings of Healthy Buildings 2000*, *Vol. 2*; Espoo, Finland, August 2000; Seppänen, O.; Säteri, J., Eds.; SIY Indoor Air Information Oy: Helsinki, 49–54.
18. Repace, J.L.; Lowrey, A.H. Indoor Air Pollution, Tobacco Smoke, and Public Health; *Science* **1980**, *208,* 464-472.
19. Thatcher, T.L.; Layton, D.W. Deposition, Resuspension and Penetration of Particles within a Residence; *Atmos. Environ.* **1995**, *29*, 1487–1497.
20. Mosley, R.B.; Greenwell, D.J.; Sparks, L.E.; Guo, Z.; Tucker, W.G.; Fortmann, R.; Whitfield, C. Penetration of Ambient Particles Into the Indoor Environment; *Aerosol Sci. Technol.* **2001**, *34,* 127-136.
21. Thatcher, T.L.; Lai, C.K.; Moreno-Jackson, R.; Sextro, R.G.; Nazaroff, W.W. Effects of Room Furnishings and Air Speed on Particle Deposition Rates Indoors; *Atmos. Environ.* **2002**, *36,* 1811-1819.
22. Wilson, W.E.; Suh, H.H. Fine Particle and Coarse Particles: Concentration Relationships Relevant to Epidemiologic Studies; *J. Air & Waste Manage. Assoc.* **1997**, *47,* 1238-1249.
23. Wilson, W.E.; Mage, D.T.; Grant, L.D. Estimating Separately Personal Exposure to Ambient and Nonambient Particulate Matter for Epidemiology and Risk Assessment: Why and How; *J. Air & Waste Manage. Assoc.* **2000**, *50,* 1167-1183.
24. Long, C.M.; Suh, H.H.; Catalano, P.J.; Koutrakis, P. Using Time- and Size-Resolved Particulate Data to Quantify Indoor Penetration and Deposition Behavior; *Environ. Sci. Technol.* **2001**, *35,* 2089-2099.
25. Hayman Fire Incident Information; 2002; Available on the U.S. Forest Service Web site http://www.fs.fed.us/r2/psicc/fire/hayres/ (accessed August 26, 2005).

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