MEASUREMENTS OF OUTDOOR AIR POLLUTION FROM SECONDHAND SMOKE ON THE UMBC CAMPUS

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Introduction.

Individual cigarettes are point sources of air pollution; smoking in groups becomes an area source. Outdoor air pollutants from individual point sources are subject to plume rise if the temperature of the smoke plume is hotter than the surrounding air; however if the plume has a small cross-section, as for a cigarette, it will rapidly cool and lose its upward momentum, and then will subside as the combustion particles and gases are heavier than air. Thus, in the case of no wind, the cigarette plume will rise to a certain height and then descend, and for a group of smokers, for example sitting in an outdoor cafe, on a hospital patio, or in stadium seats, their smoke will tend to saturate the local area with secondhand smoke (SHS). In the case where there is wind, the amount of thermally-induced plume rise is inversely proportional to the wind velocity -- doubling the wind velocity will halve the plume rise. In this case, the cigarette plume will resemble a cone tilted at an angle to the vertical. The width of the cone and its angle with the ground will depend upon the wind velocity: a higher wind will create a more horizontal but wider cone (due to increased turbulence), with uncertain impact on exposure to SHS for downwind nonsmokers. If there are multiple cigarette sources, the downwind concentrations will consist of multiple intersecting cones, i.e., overlapping plumes. As the wind direction changes, SHS pollution will be spread in various directions, fumigating downwind nonsmokers.

SHS contains a large quantity of respirable particles, which can cause breathing difficulty for those with chronic respiratory diseases or trigger an asthmatic attack in those with disabling asthma. For the remainder of nonsmokers, Junker et al. report eye, nasal and throat irritation thresholds for 24 healthy young adult females for repeated exposures over the course of 2 hours, corresponding to an SHS-$PM_{2.5}$ concentration of about 4.4 micrograms per cubic meter ($\mu g/m^3$) (Junker, 2001).

Very few published data are available on outdoor levels of SHS. A California Air Resources Board study (CARB, 2003), measured 1 and 8 hour time-weighted average nicotine concentrations outside an airport, college, government center, office complex, and amusement park, found that at these typical outdoor locations, Californians may be exposed to SHS levels previously associated only with indoor SHS concentrations. Concentrations were strongly affected by counts of the number of smokers and moderately affected by the size of the smoking area and the measured wind speed. The CARB study indicated that outdoor SHS concentrations are detectable and sometimes comparable to indoor concentrations, and demonstrates that the number of cigarettes being smoked (i.e., total source strength), the position of smokers relative to the receptor, and atmospheric conditions can lead to substantial variation in average exposures.

A more recent pilot study by Klepeis, et al. (2004) reported that mean outdoor SHS concentrations determined from field surveys of particle concentrations measured in buildings, at outdoor patios, on airport sidewalks, and in parks and public sidewalks during time periods spent in locations where smokers were intermittently active that mean SHS particle concentrations in outdoor settings in some cases can be comparable to those in indoor settings. However, mean outdoor SHS concentrations appear more variable than indoors, because outdoor SHS does not accumulate and outdoor transient peaks are more sensitive to source-receptor proximity and wind conditions.

Long-term means for outdoor SHS concentrations are averaged over a large number of transient peaks, which only occur when smokers are active, whereas indoor concentrations remain high long after cigarettes have ended, and the total dose to a person indoors from each cigarette will be greater than for a cigarette smoked outdoors. Klepeis, et al. (2004) found from controlled experiments that, during periods of smoking activity outdoor SHS levels can reach mean concentrations measured indoors, using either burning cigarettes or CO tracer gas release, and reported a decrease in mean pollutant concentrations as a function of distance such that a doubling of distance could result in a concentration reduction of up to 50% or more. At distances of 1-2 m from the source, mean outdoor SHS particle concentrations declined by about 75%. Klepeis et al. found that changing wind directions can have a large impact on outdoor SHS exposure as demonstrated by the differences between concentrations monitored on opposite sides of an active point source.

The plume is driven in the longitudinal direction by the wind, and in the transverse directions by diffusion. A highly simplified expression which illustrates the physics for the downwind concentration C <u>on the plume line</u> for a point source pollutant emitted at ground level is given by: $C = Q/k_y k_z x$, where Q is the pollutant mass emission rate, x is the longitudinal distance from the source to the receptor, and where the product $k_y k_z$ represents the diffusion constants in the transverse vertical and horizontal planes which describe the increasing lateral spread of the pollutant concentration as it proceeds downwind in the longitudinal direction. There are four key features of most models which describe the dispersal of emissions from a point source at ground level:

1. The downwind concentration at any location is directly proportional to the mass emission rate of the source.
2. The more turbulent the atmosphere, the more rapid the spread of the plume in the direction transverse to the direction of propagation of the plume.
3. The maximum concentration at ground level is directly downwind on the plume line, and is inversely proportional to the downwind distance from the source.
4. The maximum concentration decreases for higher wind speeds, even though on the plume line there is no explicit dependence on wind speed, because the diffusion constants $k_y k_z$ are inversely proportional to wind speed, due to mechanical turbulence. These empirically-determined constants also depend on the vertical temperature gradient of the atmosphere, which determines the

> temperature difference between a rising parcel of plume air and the surrounding air. (Williamson, 1973)

Thus, for each point source, the plume concentration will increase with source strength, and decrease with increasing distance from the source and with increasing wind speed. However, for a very large area source, while the pollutant concentration downwind will still decrease inversely as the wind speed, it will *increase* with downwind distance from the source as the square root of distance, or if there is an atmospheric inversion, with increase linearly with distance.

With these considerations in mind, a field study and two controlled experiments were designed and implemented on the campus of the University of Maryland at Baltimore's (UMBC) Catonsville, MD campus, at the request of UMBC's University Health Services, to perform experiments designed to quantify secondhand smoke levels outdoors in the vicinity of building entrances, in order to provide scientific data relating to whether limitations on smoking in proximity to campus building entrances were justified.

Biographical Sketch of the Principal Investigator. I am a biophysicist and an international secondhand smoke consultant with more than 60 scientific papers published on the hazard, exposure, dose, risk, and control of secondhand smoke. I have received the Flight Attendant Medical Research Institute Distinguished Professor Award, the Robert Wood Johnson Foundation Innovator Award, the Surgeon General's Medallion, and a Lifetime Achievement Award from the American Public Health Association. I am a Visiting Assistant Clinical Professor at the Tufts University School of Medicine. I was a senior policy analyst and scientist with the U.S. Environmental Protection Agency. I served as a consultant to the Occupational Safety and Health Administration, U.S. Department of Labor, on its proposed rule to regulate secondhand smoke and indoor air quality. I was also a research physicist at the Naval Research Laboratory in the Ocean Sciences and Electronics Divisions. My full CV may be viewed at www.repace.com.

The UMBC Outdoor Secondhand Smoke Studies.

Equipment and Methodology.

I deployed continuous real-time monitors for respirable particles (RSP), i.e., airborne particulate matter in the combustion size range below 3.5 microns in diameter ($PM_{3.5}$), and carcinogenic particulate polycyclic aromatic hydrocarbons (PPAH), which are appropriate markers for secondhand smoke and its toxicity. In addition I monitored carbon dioxide (CO_2), carbon monoxide, temperature, and relative humidity. For SHS tracer monitoring, I used real-time battery-powered instruments, including the active-mode MIE personalDataRAM (pDR-1200) and the EcoChem PAS 2000CE, a real-time respirable PPAH monitor. Outdoors, the major sources of PPAH particles are diesel exhaust and cars with defective catalytic converters. PPAH particles are submicron in size, or "nanoparticles." The calibration and deployment of these instruments is described in Repace (2004). The monitoring instruments were synchronized to each other and to a wrist watch. A time-activity diary was used to record location and clock-time from the watch at that location for comparison to the RSP and PPAH data measured at various locations on the UMBC campus in the studies described below.

Results.

On April 5th and 14th, I performed one field study and two sets of controlled experiments, as summarized in the figures below. Figure 1 illustrates the effect of a light and heavy breeze on a cigarette smoke plume. Figure 2 illustrates the effect of no breeze on the cigarette plume, which rises and disperses until it cools and subsides (Repace, 2000).

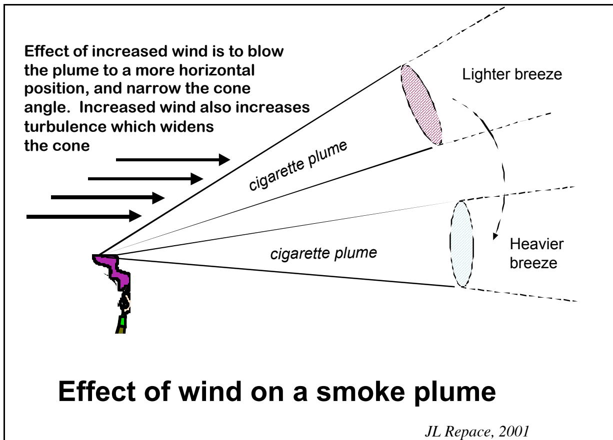

Figure 1. Plume cones in light & heavy breezes.

Figure 2. Plume rises & falls with no breeze.

Figure 3 shows a plot of the real-time data measured on the UMBC campus for RSP ($PM_{3.5}$) in units of micrograms per cubic meter (μg/ m^3) on the left axis, and PPAH concentrations in nanograms per cubic meter (ng/m^3) on the right axis, as a function of elapsed time in minutes (lower horizontal axis) and clock time (upper horizontal axis). The PPAH monitor was housed in a camera bag mounted on top of a small wheeled suitcase which housed the RSP monitor. The intakes and exhausts of the concealed monitors were connected to the outdoor environment.

The monitors were deployed about the UMBC campus in a variety of locations on Tuesday, April 5th, 2005, including indoors in the Health Services conference room, outdoors where smokers were briefly encountered between the Mathematics and Psychology Buildings between 12:45 and 1:00 PM, on the Commons Building Plaza near the cafeteria entrance, and at various distances in the Plaza. A controlled experiment using 5 smoldered cigarettes was conducted between 2:20 and 2:40, to simulate the effect of smokers outside the cafeteria entrance to the Commons building. The smoldered cigarettes each emit about 90% of the smoke a smoked cigarette. In all cases, the point sources of smoking were subject to breezes blowing in various directions from West-Southwest to North-Northwest from 3 to 7 mph. The study ended at about 3:10 PM. It is seen that in the proximity of smokers, both RSP and PPAH peaks are elevated well above background concentrations.

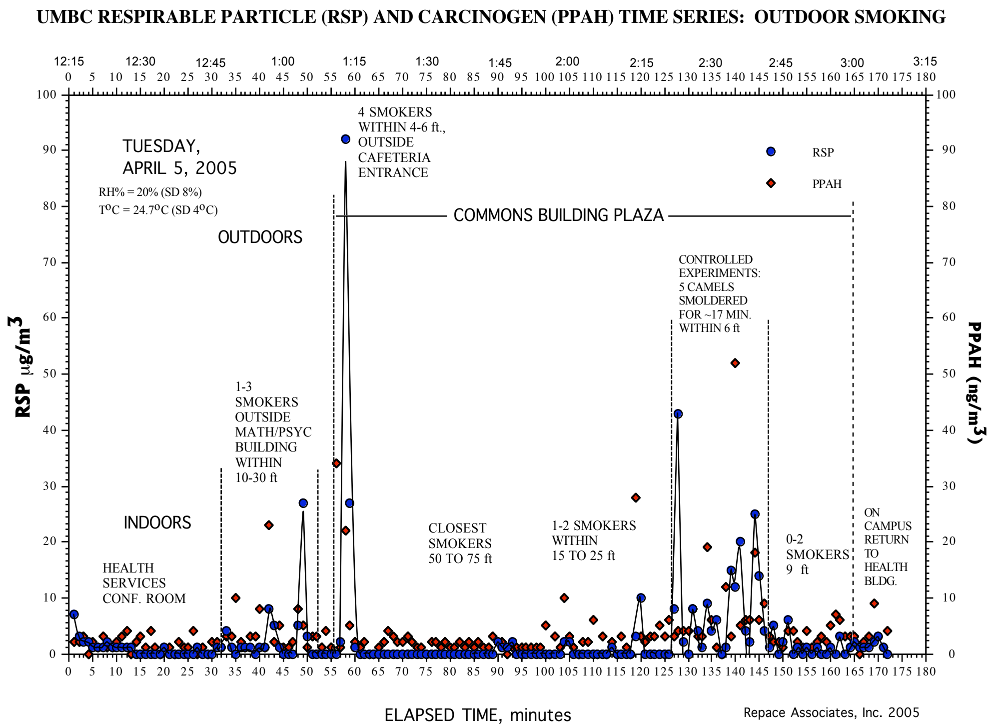

Figure 3. April 5th field study. Winds were light 3-7 mph, blowing WSW-NNW. One indoor location and several outdoor locations were sampled with smokers in close and distant proximity. A controlled experiment with cigarettes located at a point source was conducted for comparison.

April 15th Controlled Experiments.

A series of experiments were conducted on Thursday, April 14th to measure the concentration of SHS as a function of distance from the source. Based on the results of the controlled experiment of April 5th, to eliminate variation in concentration due to changes in wind direction during the time it takes to smoke a cigarette, the source was arrayed in a ring at 8 -10 points around the compass, so that no matter which way the wind blew, the monitors would pick up the smoke-plume. Up to 10 smokers were recruited by UMBC Health Services, and they smoked at 3 distances as shown in Experiments I (1-2 smokers only), III (9-10 smokers), and IV (10 smokers). Experiments II, V, and VI were conducted with smoldered Marlboro Medium Cigarettes only for comparison. Initially (Experiment I) 2 smokers were set up upwind of the monitors at 2 compass points. The levels are little different from 8 smoldered cigarettes at the same distance (Experiment II). Similarly, there is little difference between 8 smoldered cigarettes at 1.5 meters and 9.4 smokers at 2 meters. Figure 4 shows the experimental design overlaid on the smokers sitting in chairs around the centrally-located monitor.

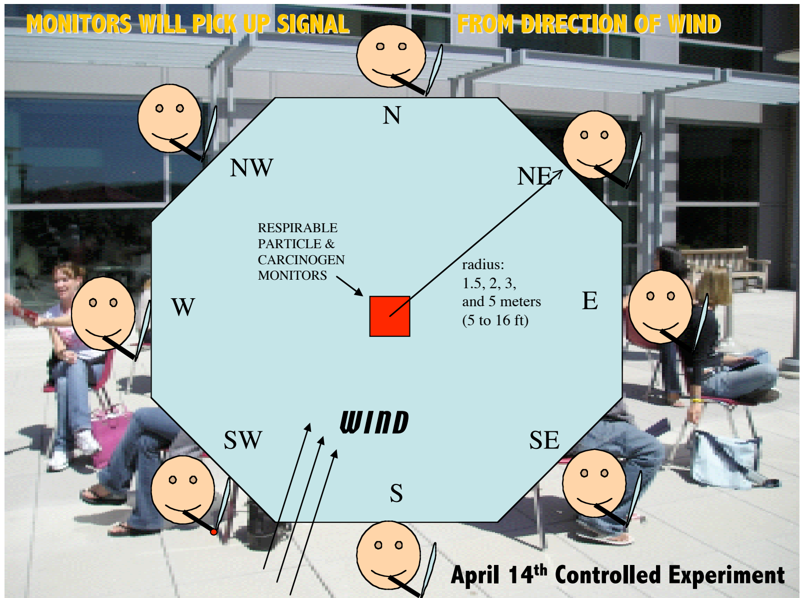

Figure 4. Controlled experiment of April 14th involved simulating an area source, by locating smokers or smoldered cigarettes on chairs in a ring around the PAH and RSP monitors. The ring radius was started at 1.5 meters, and increased in steps to 2, 3, and 5 meters. A meter represents 3.28 feet. No matter which direction the wind blows from, the receptor will always be downwind.

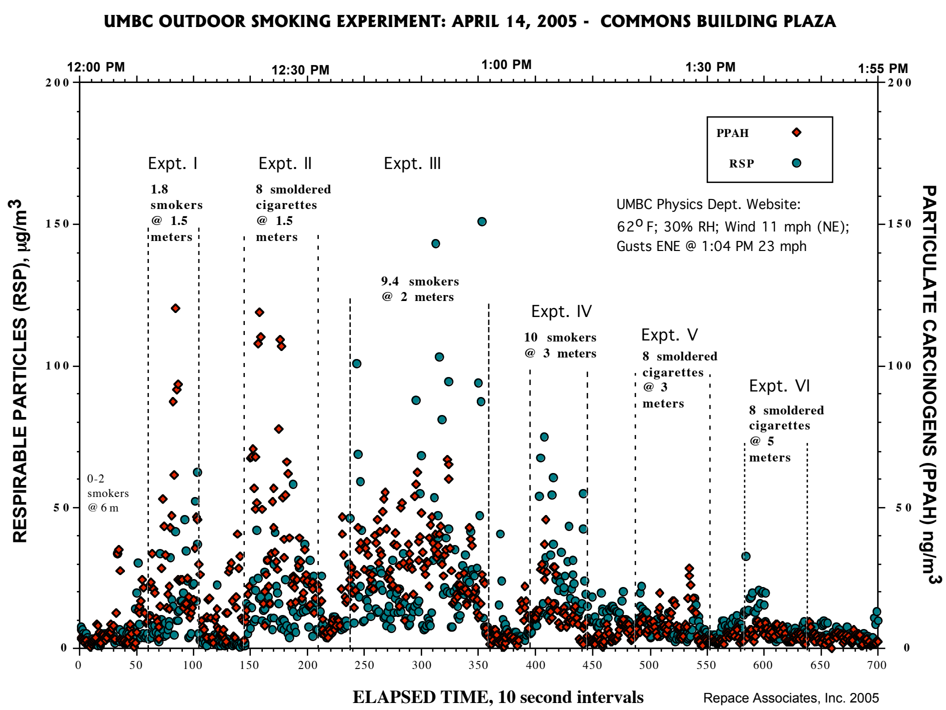

Figure 5. April 14th field study. The diamonds represent the PPAH data in ng/m^3, and the circles represent the RSP data in μg/m^3. One indoor location and several outdoor locations were sampled with smokers in close and distant proximity. A controlled experiment with cigarettes located at a point source was conducted for comparison.

Figure 5 shows the data for RSP and PPAH for each of the experiments as the ring diameter is increased. Figure 5 shows the data for each of the experiments as a function of time, numbers of smokers or cigarettes, and ring diameter. RSP is shown on the right-hand vertical axis, PPAH on the left-hand vertical axis, and the ring-radius (i.e., the smoker-to-monitor distance) is shown on the horizontal axis. Figure 6 shows a plot of the 3 smoldered cigarette experiments (II, V, and VI); an approximately inverse dependence of SHS-RSP concentration with source-receptor distance is displayed, while the PPAH concentration decays approximately as the square of the distance. In controlled experiments indoors, Repace (2004) observed that PPAH concentrations decreased approximately twice as fast as SHS-RSP. Figure 7 plots all of the experiments (I-VI) together, adding the smokers to the smoldered cigarettes. There is considerably more scatter in the data, likely due to the more erratic pattern of smoking by real smokers than for smoldered cigarettes. Nevertheless the same dependence with distance emerges from the curve fits. Neither concentration appears to get close to background until a distance of greater than 7 meters is reached.

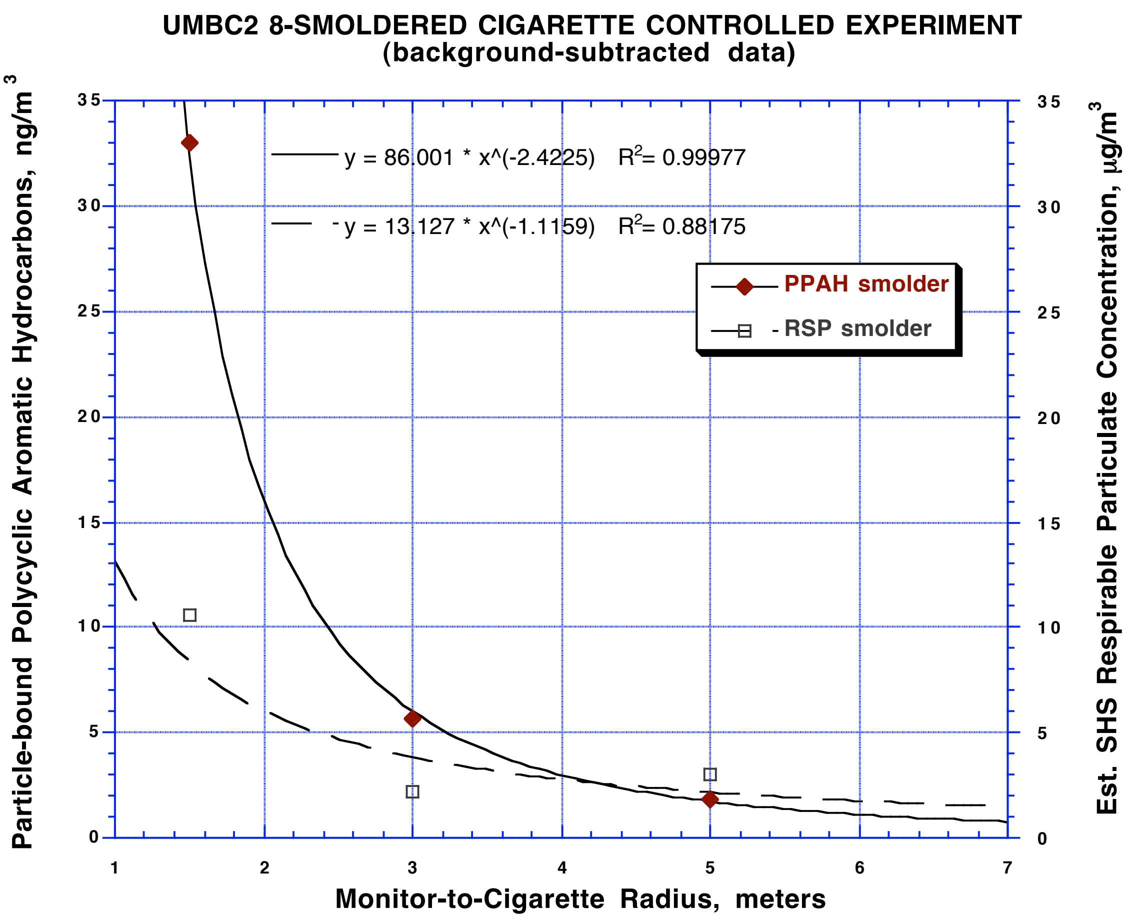

Figure 6. April 15th Experiment. Smoldered cigarettes (Marlboro Medium 100s, filtered) located at 8 equally spaced compass positions at ring radii 1.5, 3, and 5 meters. Curve fits to the PPAH and RSP curves are shown, and extrapolated to 7 meters (23 feet). PPAH declines as the inverse square of the source-receptor distance *x*, whereas RSP declines inversely as the distance, as expected.

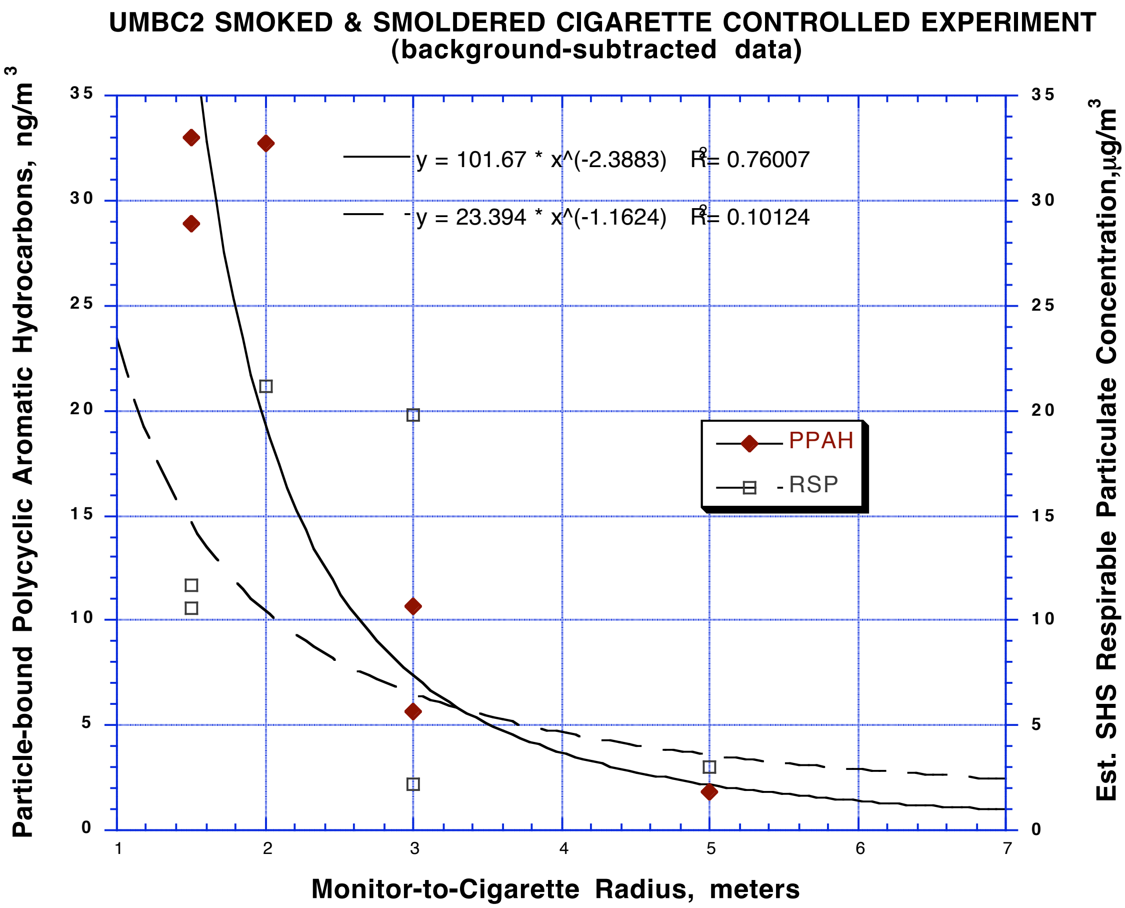

Figure 7. Smoked cigarettes at 1.5, 2, and 3 meters overlayed on the smoldered cigarette plot of figure 5 with curve fits to the combined PPAH and RSP data, extrapolated to 7 meters (23 feet). Although there is more scatter in the data when the smokers are added, approximately the same dependence of PPAH and RSP with distance is seen.

Discussion. What levels of SHS constitute clean air? $PM_{2.5}$ is the RSP size range that encompasses combustion-related fine particulate by-products such as tobacco smoke, chimney smoke, and diesel exhaust. $PM_{2.5}$ is legally regulated in the outdoor air. In 1997, the EPA promulgated a 24-hour U.S. Annual National Ambient Air Quality Standard (NAAQS) for RSP for particulate matter $PM_{2.5}$. The NAAQS for $PM_{2.5}$ of 65 $\mu g/m^3$, also limited by an annually averaged NAAQS for $PM_{2.5}$ of 15 $\mu g/m^3$, based on protecting human health. The NAAQS for $PM_{2.5}$ is designed to protect against such respirable particle health effects as premature death, increased hospital admissions, and emergency room visits (primarily the elderly and individuals with cardiopulmonary disease); increased respiratory symptoms and disease (children and individuals with cardiopulmonary disease); decreased lung function (particularly in children and individuals with asthma); and against alterations in lung tissue and structure and in respiratory tract defense mechanisms in all persons. $PM_{2.5}$ and $PM_{3.5}$ (measured in this study) are closely-related RSP fractions, especially for the submicron SHS aerosol. Table I shows the federal Air Quality Index and the associated color-coded advisories.

While these have averaging times associated with them, the levels may be used to infer whether a given peak in figures 2 and 4 represent high or low levels of pollution. Each of these figures shows levels as high as 100 to 150 $\mu g/m^3$ outdoors in proximity to smokers, indicating that the air is in the unhealthy or Code Red range. Moreover, secondhand smoke causes a number of acute symptoms (eye, nose, and throat irritation, headaches, dizziness, and nausea) and chronic diseases (lung and nasal sinus cancer and heart disease) (CARB, 2003). Levels of irritation begin as low as 4 $\mu g/m^3$ SHS-RSP and levels of odor detection are as low as 1 $\mu g/m^3$ (Junker et al. 2001). Thus SHS odor would be detectable in our experiments as far as 7 meters from the source, and levels of irritation would begin at 4 meters from the source.

As for the PPAH carcinogens, Figures 2 through 6 show clearly that for this pollutant, levels close to smokers are elevated above background by up to 2 orders of magnitude (a factor of 100), relative to distances beyond 7 meters. Thus, it is clear that tobacco smoke pollution outdoors at significant distances from smokers must be considered as significantly unhealthy. Thus, while students or faculty asthmatics pass through a cloud of smoke, levels might be sufficient to trigger an attack, and certainly are high enough to pose a nuisance to all. Moreover, smoking in proximity to doorways or air intakes might easily be inducted into the building through posing both acute and chronic threats to building occupants.

Table 1. Levels of fine particulate ($PM_{2.5}$) air pollution and corresponding federal health advisory descriptors with accompanying simplified color code (US EPA, 1999).

$PM_{2.5}$ ($\mu g/m^3$) AQI Break-points	Air Quality Index	Category	Color Code
0.0 - 15.4	0 - 50	Good	Green
15.5- 40.4	51 - 100	Moderate	Yellow
40.5 - 65.4	101 -150	Unhealthy SG*	Orange
65.5 - 150.4	151 - 200	Unhealthy	Red
150.5 - 250.4	201 - 300	Very unhealthy	Violet
250.5 - 350.4	301 - 400	Hazardous	Maroon
350.5 - 500.4	401- 500	Very Hazardous	Maroon
> 505	500	**(Significant Harm)****	

*SG = sensitive groups; **exists, but is not a part of the AQI. Source U.S. EPA, 1999. [GUIDELINE FOR REPORTING OF DAILY AIR QUALITY - AIR QUALITY INDEX (AQI) United States Office of Air Quality EPA-454/R-99-010 Environmental Protection Planning and Standards July 1999 Agency Research Triangle Park, NC 27711].

Conclusions.

These experiments dispel the common misconception that smoking outdoors can be ignored because smoke plumes immediately dissipate into the environment. These controlled experiments with and without smokers show similar results: if a receptor such as a doorway, air intake, or an individual is surrounded by an area source – and this would include an entranceway with a group of smokers standing nearby – then regardless of which way the wind blows, the receptor is always downwind from the source. Cigarette smoke RSP concentrations decline approximately inversely with distance downwind from the point source, as expected, whereas cigarette smoke PPAH concentrations decline faster, at approximately inversely as the square of this distance.

Based on these measurements, which involve a single ring of cigarettes or smokers, the smoke levels do not approach background levels for fine particles or carcinogens until about 7 meters or 23 feet from the source, which is likely to be the smoke from no more than 1 or 2 smokers. Greater numbers of smokers in the area could lead to higher concentrations. because a crowd of smokers constitute an area source, whose plumes may overlap downwind, potentially causing smoke concentrations to increase locally before dissipating at greater distances. Secondhand smoke causes a number of acute symptoms (eye, nose, and throat irritation, headaches, dizziness, and nausea) and chronic diseases (lung and nasal sinus cancer and heart disease). Students or faculty passing through the cloud of smoke would encounter detectable levels at about 7 meters (23 feet) from a smoker, and irritating levels at 4 meters (13 feet). Moreover, smokers in proximity to a doorway as persons enter or depart, may result in smoke being inducted into the building, posing a chronic threat as well as an acute one, to building occupants. Therefore it makes sense to post signs warning smokers not to smoke closer than about 20 feet from building entrances, and to place ashtrays at that distance and no closer. Moreover, because some persons suffer from severe asthma, and secondhand smoke is a known asthmatic trigger, this is another good reason to keep smokers from congregating closer to building entrances than 20 feet.

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