FAST TRACK ARTICLE

Respirable Particles and Carcinogens in the Air of Delaware Hospitality Venues Before and After a Smoking Ban

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How do the concentrations of indoor air pollutants known to increase risk of respiratory disease, cancer, heart disease, and stroke change after a smoke-free workplace law? Real-time measurements were made of respirable particle (RSP) air pollution and particulate polycyclic aromatic hydrocarbons (PPAH), in a casino, six bars, and a pool hall before and after a smoking ban. Secondhand smoke contributed 90% to 95% of the RSP air pollution during smoking, and 85% to 95% of the carcinogenic PPAH, greatly exceeding levels of these contaminants encountered on major truck highways and polluted city streets. This air-quality survey demonstrates conclusively that the health of hospitality workers and patrons is endangered by tobacco smoke pollution. Smoke-free workplace laws eliminate that hazard and provide health protection impossible to achieve through ventilation or air cleaning. (J Occup Environ Med. *2004;46:887–905*)

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DOI: 10.1097/01.jom.0000141644.69355.52

Secondhand smoke (SHS), ie, indoor air pollution from tobacco combustion, has been condemned as a health hazard by all US occupational health, environmental health, and public health authorities, and smoking has been prohibited in all federal workplaces.[1–8] Nevertheless, because of repeated Congressional admonitions that SHS is an issue best handled by the States, for the last decade, US federal regulatory agencies have been actively discouraged from further rulemaking or research efforts to protect private-sector workers and the public. However, the States have been slow to take action, especially in the hospitality industry sector. Maryland Occupational Safety and Health banned smoking in all workplaces in 1994, but in 1995, the State legislature overrode the rule before it took effect, exempting bars and restaurant bars, apparently in the belief that hospitality industry workers did not warrant the same protection from SHS as other workers. In 1995, California banned smoking in all restaurants and other workplaces and in 1998 extended the ban to include all bars. Delaware's bar ban was passed in 2002. By mid-2004, Maine, Massachusetts, Rhode Island, Connecticut, and New York also had banned smoking in all workplaces, including hospitality venues, bringing the fraction of states affording all workers complete protection from SHS to just 14%.

The improvement in air quality afforded by California's all-workplace smoking ban provided imme-

TABLE 1
Eight Wilmington, Delaware, Hospitality Venues in Which Air Quality Measurements Were Made

Venue	Description
A. Casino	Large-volume slot machine-only casino with restaurant/bar areas, all smoking; One relatively small non-smoking area prior to the ban. Monitors circulated around periphery of central salon during smoking tour; during nonsmoking tour, monitors located in outer portion of coat-check room open to surrounding air through large window.
B. Bar/Restaurant	Standup/sit-down smoking bar area with adjacent dining table area; located in a mid-size shopping mall with an outdoor entrance. Monitors on both smoking and nonsmoking tours located in same location at end of bar area.
C. Bar/Restaurant	Large volume nonsmoking restaurant with entertainment section; caters to families, but with a fenced-off bar-area (the only smoking area prior to the ban). Monitors located inside bar area at periphery at same location on both visits.
D. Bar/Restaurant	Sit-down smoking bar; open passage to dining area; genteel sports-bar-like atmosphere. Monitors located at same spot ~6 ft from vestibule at one end of bar area on both visits.
E. Bar/Restaurant	Large sit-down upscale smoking bar surrounded by smoking dining tables with adjacent dance floor. No cover charge; serves singles, couples, and parties. Monitors located between barstools in proximate locations on each visit.
F. Bar/Restaurant	Sit-down smoking bar with large adjacent nonsmoking restaurant area for dining. Monitors located on opposite sides of one end of bar area on each visit.
G. Stand-up Bar	Stand-up smoking bar with adjacent dance floor primarily catering to college or college-age singles; very crowded. Cover charge was requested of all patrons. Monitors located ~6 ft from front door and on opposite sides for each visit. Door was frequently opened as persons entered or left premises. Several patrons smoked outside the door during the nonsmoking tour.
H. Pool Hall	Standup/sit-down smoking bar contiguous to adjacent smoking pool hall; mostly working class adult patrons. Monitors located on periphery of pool table area during smoking tour; at a nearby pool table during the nonsmoking tour.

Areas described as "Smoking" allowed smoking on November 15, 2002, and did not allow smoking on January 24, 2003, after the ban. Alphabet letters before Venue descriptions are keyed to Figures 3 and 6. All restaurant areas were nonsmoking on both dates unless otherwise specified. These venues were chosen from across the spectrum of available hospitality types.

diate respiratory health benefits for bartenders, according to a study of SHS exposure and respiratory symptoms in a cohort of 53 bartenders before and after the ban.[9] Forty-five percent of the bartenders were current smokers who reported no overall change in smoking habits subsequent to the prohibition. Seventy-four percent of the bartenders initially reported respiratory symptoms; of those with symptoms before the ban, 59% had no symptoms after the ban. Seventy-seven percent reported sensory irritation before the ban; after the ban, 78% of these had symptom resolution. Interestingly, after workplace SHS exposure ceased, pulmonary function tests showed a marked 5% to 7% improvement after only 1 month of smoke-free air, for both nonsmokers *and* smokers.[9] This study raises general questions as to how high contemporary hospitality industry SHS air pollution levels might be, how they compare to outdoor air pollution, what reductions in indoor air pollution might result from a smoking ban, whether such reductions in exposure could have been achieved by engineering measures such as ventilation or air cleaning, and what relative health benefits might result from engineering versus source controls. The hospitality industry, the ventilation industry, and the tobacco industry have aggressively promoted ventilation or air cleaning as viable and preferable alternatives to smoke-free workplace laws all over North America and abroad.

Accordingly, for the first time, an air quality study has been conducted before and after the enactment of a statewide Clean Indoor Air Law. An opportunity presented itself in late 2002, with the implementation of such a law in the State of Delaware, whose population was 780,000 in 2000. Effective November 27, 2002, the *Delaware Clean Indoor Air Act* was amended to ban smoking in restaurants, bars, and casinos, hospitality venues that were excluded in the original Act passed by the General Assembly in 1994. The 2002 Amendment was intended to give hospitality workers the same occupational health protection that workers in other sectors already enjoyed. The law is administered by the State Health Department, which received requests from businesses for exemptions to the rules based on putative economic or libertarian grounds. Opponents threatened a repeal of the amended Act when the legislature re-convened in 2003.[10]

Therefore, to assess the impact of SHS on workers and patrons, the Delaware Tobacco Prevention Coalition commissioned the author to monitor indoor air quality in a casino, six bars, and a pool hall (Table 1) under both smoking and nonsmoking conditions. All venues were located in the Wilmington metropolitan area, about 30 miles south of Philadelphia, in a county with 64% of the state's population. I conducted the first phase on

Friday evening, November 15, 2002, before the smoking ban, and the second on Friday evening, January 24, 2003, after smoking ban compliance had been demonstrated. Concealed monitors for respirable particles (RSP), ie, airborne particulate matter in the combustion size range less than 3.5 μm in diameter ($PM_{3.5}$), and carcinogenic particulate polycyclic aromatic hydrocarbons (PPAH) were deployed. Cigarettes, pipes, and cigars are major emitters of both RSP and PPAH.[11–13] This report describes the Delaware air quality survey and its results.

Part I: Determinants of SHS Concentrations

Unless they constitute a statistically valid random sample, simply measuring atmospheric tracers for SHS in the presence of smoking without characterizing the basic parameters that determine those concentrations, as do many field studies of SHS, makes them difficult or impossible to generalize, and therefore of limited value. Concentrations of SHS are directly proportional to the smoker density and inversely proportional to the air exchange rate.[11] Thus, at fixed air exchange and smoking rates, one cigarette smoked in a large room will yield a lower SHS concentration than one smoked in a small room. However, by measuring concentration and smoker density, it is possible to normalize for this effect and generalize the results. Smoker density can be determined by measuring the average number of cigarettes smoked during the observation time and dividing by the space volume. The total or "effective" air exchange rate[11] is defined as the sum of pollutant removal by ventilation, surface deposition, and air cleaning (if any). Most restaurants and bars use mechanical ventilation. North American mechanical ventilation rate design values are specified by the Atlanta, Georgia-based American Society of Heating, Refrigeration, and Ventilation Engineers (ASHRAE). ASHRAE Standard 62–1989, *Ventilation for Acceptable Indoor Air Quality*, specified ventilation rates for odor control "to accommodate a moderate amount of smoking" for premises in which smoking was allowed.[29] Importantly, these design ventilation rates are based upon building occupancy, ie, number of occupants per unit floor area. For a given smoking prevalence, this determines the number of smokers per unit floor area, and for a given ceiling height, the smoker density. Thus, for a specific venue, eg, a bar, the default design occupancy from the ASHRAE Standard can be used to estimate both the smoker density and the ventilation air exchange rate.

Subsequent editions of ASHRAE Standard 62 issued since 1999 no longer recommend ventilation rates for smoking buildings, and contain the caveat that "since 1989, numerous cognizant authorities have determined that environmental tobacco smoke is harmful to human health." However, Standard 62–2001 has the same hospitality industry design ventilation rates as Standard 62–1989. Thus, SHS concentrations can be predicted and used to generalize measured concentrations by mathematical models incorporating statewide smoking prevalence, default occupancy and ventilation rates specified for bars, game rooms, and casinos. If ventilation rates are not measured in a field study, to properly interpret measured SHS concentrations, the area, volume, and average number of cigarettes smoked should be recorded, and air exchange rates may then be estimated using the mass balance model and compared to ASHRAE design rates.[11,27,28] In order to place this study into perspective, a series of calculations is performed below to estimate the typical venue's air exchange rates from the ventilation rates prescribed by the ASHRAE Standard, and to predict the corresponding expected SHS concentrations at the ASHRAE default occupancy and current Delaware state smoking prevalence from the time-averaged mass balance model, discussed below.[11,27,28]

ASHRAE Standard 62–1989/2001 Default Design Ventilation Rate and Building Occupancy

Recommended outdoor air supply rate for bars: 30 cubic feet per minute per occupant (cfm/occ or ft^3/min-occ); maximum (default) occupancy, 100 persons per 1000 ft^2 of floor area. Recommended outdoor air supply rate for casinos: 30 cfm/occ for outdoor ventilation air, for a maximum occupancy of 120 persons per 1000 ft^2. For a pool hall that contains a bar (as does the pool hall in this study), the default is assumed to be the same as for a bar; recommended outdoor air supply rate for game rooms is close, at 25 cfm/occ, for a maximum occupancy of 70 persons per 1000 ft^2.

Predicted Design Ventilation Air Exchange Rates

Assuming a 10-foot ceiling, the default design air exchange rate for a bar is: C_v = (30 ft^3/min-occ)(100 occ/10,000 ft^3)(60 min/h) = 18 air changes per hour (h^{-1}). For a casino of ceiling height of 14 ft, the default air exchange rate is estimated as C_v = (30 ft^3/min-occ)(120 occ/14,000 ft^3)(60 min/h) = 15 h^{-1}.

Predicted Active Smoking Prevalence

The 2002 estimated average Delaware adult smoking prevalence is 23%.[30] Thus, for a large group of Delaware adults encountered at random, eg, in a casino, about 23% would be expected to be smokers. However, the physically observable parameter in a field survey of smoking behavior is not the actual number of smokers, which is generally unknown, since they all do not smoke simultaneously. Rather, one counts the average number of burning cigarettes smoked during the observation period, ensuring that the counting interval is comparable with the typical cigarette smoking time (about 10 min). In any group of habitual smokers (ie, smoking 2 cigarettes per hour and 10 min per cigarette),[11] approximately one third of the smokers would be expected to be observed actively smoking at any one time.[11,27,52] Thus in a field survey in Delaware, the number of active smokers, ie, burning cigarettes, n_s, would be expected to be one third of 23% or approximately 7.7% if the smoking prevalence is representative of the prevalence in the larger Delaware population. Furthermore, if one walks into a bar, counts the number of burning cigarettes every 10 minover the course of a half hour as 2, 4, and 3, and averages them as $n_s = (2 + 4 + 3)/3 = 3$, then the estimated number of habitual smokers would be $n_{hs} = 3n_s = 9$.

Predicted Active Smoker Density

If a bar has a percentage of smokers equal to the current Delaware prevalence, the default habitual smoker density is (0.23 smokers/occ)(100 occ/10,000 ft^3) = 23 smokers per 10,000 ft^3, or in metric units, 23 smokers per 283 cubic meters (m^3), of whom one third would be expected to be actively smoking at any one time,[11] which yields a predicted active smoker density of $D_s = (1/3)(23)/2.83 = 2.7$ active smokers per 100 m^3. At the default smoking prevalence of 23%, a casino would have a default habitual smoker density of (0.23 smokers/occ)(120 occ/14,000 ft^3) = 19.7 smokers per 10,000 ft^3, corresponding to an active smoker density of $D_s = (1/3)(19.7)/2.83 = 2.32$ active smokers per 100 m^3.

The SHS-RSP Habitual Smoker Model (HSM)

The HSM (Equation 1) is used to predict SHS concentrations. The model coefficient (650) was derived by curve-fitting in a controlled experiment in a ventilated conference room using four active smokers;[11,27] it is structurally identical to the more general time-averaged mass-balance model of Ott et al.[34] An updated derivation[52] shows that the assumptions of HSM are consistent with a 14 mg per cigarette (mg/cig) RSP emission and a default surface deposition term equal to 30% of the ventilatory air exchange rate. Equation 1 gives the SHS-RSP concentration, in units of micrograms of pollutant per cubic meter of air ($\mu g/m^3$), as a function of the active smoker density D_s, in units of average number of burning cigarettes per hundred cubic meters (BC/100m^3) in the building and the air exchange rate C_v, in units of air changes per hour (h^{-1}):[11,27]

$$RSP_{ETS} = 650 \frac{D_S}{C_v} (\mu g/m^3) \quad (1)$$

Using Equation 1, the predicted RSP concentration ($PM_{3.5}$) for a Delaware bar under the ASHRAE default assumptions for occupancy and ventilation, and the Delaware smoking prevalence is calculated as:

$SHS-RSP_{pub} = 650(2.7)/(18) = 98\ \mu g/m^3$.

Assuming a background RSP concentration of 17 $\mu g/m^3$ from outdoor non-SHS sources infiltrating indoors (see below), a field study of fine particle pollution from smoking in the ASHRAE-default occupied and ventilated pub (full occupancy, average smoking prevalence, and ASHRAE Standard ventilation rate) might be expected to show an estimated total RSP concentration of about (98 + 17) 115 $\mu g/m^3$. For the ASHRAE-default occupied and ventilated casino (full occupancy, average smoking prevalence, and ASHRAE Standard ventilation rate), the predicted level above background is calculated to be:

$SHS-RSP_{casino} = 650(2.32)/(15) = 101\ \mu g/m^3$,

which becomes a total estimated RSP level of 118 $\mu g/m^3$ with the same RSP background added.

These predictions will serve as ballpark numbers to expect in a field study, and as a basis for generalizing the results of the field study to similar venues that may have different smoker densities or air exchange rates. If the smoker density in a particular venue is lower—or the air exchange rate higher—than the default calculation, the actual concentration will be lower; if the smoker density is higher or the air exchange rate lower, the actual concentration will be higher.

The U.S. Annual National Ambient Air Quality Standard (NAAQS) for RSP

To place the predicted and observed levels of RSP into perspective, consider the NAAQS for particulate matter 2.5 μm in diameter or less ($PM_{2.5}$). $PM_{2.5}$ is the RSP size range that encompasses combustion-related fine particulate byproducts 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-h 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.[31,32] 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.[30] $PM_{2.5}$ and $PM_{3.5}$ (measured in this study) are closely related RSP fractions, especially for the submicron SHS aerosol.[11,14,41]

Comparison of Predicted Levels With Federal Air Quality Standards

Because the NAAQS incorporates an averaging time, a worker will be assumed to be exposed to RSP from SHS on the job one third of the day for 250 days per year and to background RSP only for all 365 days per year because RSP from outdoors penetrates readily into buildings.[14] The RSP background level can be determined from federal outdoor air quality data. Wilmington, Delaware's largest city, has a population of 73,000, is a hub for the chemical and shipping industries and is located in New Castle County, which has a federally monitored outdoor air quality monitoring network. Data from this network show that New Castle is listed by the EPA as one of the counties whose outdoor fine-particle air pollution level violates *de jure* the NAAQS for $PM_{2.5}$, with an average of 16.6 $\mu g/m^3$ during the 3-year period, 1999 to 2001 (List 1: Counties Exceeding the $PM_{2.5}$ NAAQS, M. Schmidt, US EPA www.epa.gov/s97is.vts) For the basis of comparison, the New Castle County annual average $PM_{2.5}$ level will be chosen as background. Thus, assuming ASHRAE default values, a Delaware hospitality worker would be exposed to an on-the-job SHS-RSP exposure of $\sim$100 $\mu g/m^3$ for 250 days per year and to a 24-h background level of 16.6 $\mu g/m^3$ for all 365 days per year. The worker's annual average total RSP exposure is estimated as: $[(1/3)(100\ \mu g/m^3)(250\ days/y) + (16.6\ \mu g/m^3)(365\ days/y)]/365\ days/y = (22.8 + 16.6) = 39\ \mu g/m^3$. This exceeds the NAAQS by a factor of $(39/15) = 2.6$. Thus, at average smoking prevalence and full occupancy, plus ASHRAE ventilation rates, a hospitality worker would breathe unclean air, ie, air quality that *de facto* violates the health-based NAAQS.

How Much Ventilation Would Be Required to Meet the NAAQS?

To satisfy the NAAQS *de facto*, a worker's weighted annual average exposure would have to be $\leq$15 $\mu g/m^3$. Assume that instead of 16.6 $\mu g/m^3$, the annual average outdoor RSP level were as low as 10 $\mu g/m^3$. Then, if X is the maximum concentration of SHS-RSP that would satisfy the 15 $\mu g/m^3$ NAAQS requirement, then the following equation holds: $[(1/3)(X \mu g/m^3)(250\ days/y) + (10\ \mu g/m^3)(365\ days/y)]/365\ days/y = (0.228\ X + 10\ \mu g/m^3) = 15\ \mu g/m^3$. Solving for X yields: $X = 650\ D_s/C_v \leq 22\ \mu g/m^3$. For a bar with a Delaware average smoking prevalence, $D_s = 2.7$. Solving the inequality for the critical air exchange rate yields $C_v \geq (650)(2.7)/22 \geq 80$ air changes per hour (ach), equivalent to $(80/18)(30\ cfm/occ) = 133\ cfm/occ$, a 4.4-fold increase over ASHRAE's 30 cfm/occ recommendation. (N.B., particulate air cleaners are subject to the same calculation, but are ineffective for gas-phase contaminants, unlike ventilation systems, which exhaust part of the recirculated air outdoors, which removes SHS gases.) Suppose the outdoor air level were to average 14 $\mu g/m^3$? In that case, re-doing the calculation above shows that the required bar air exchange rate C_v increases to 400 $hours^{-1}$ (665 cfm/occ) to satisfy the NAAQS *de facto* for the bar workers. At the actual 16.6 $\mu g/m^3$ outdoor air average, the NAAQS can *never* be attained unless the outdoor air supply is cleaned with a fine particle filter. This calculation illustrates the futility of engineering controls for SHS, without even considering its carcinogenic properties.

Part II: SHS Measurement Methods

RSP

RSP was chosen in part because there are relevant recently promulgated federal health-based outdoor air quality standards for a very similar fraction of RSP, $PM_{2.5}$,[14,15] and in part because there are real-time personal exposure monitors for RSP. EPA's outdoor air standards are widely accepted as a basis for judging the quality of indoor air.[14] $PM_{3.5}$ also was selected in part to compare directly to previously published $PM_{3.5}$ measurements of tobacco smoke pollution by this and other investigators.[11] Many epidemiologic studies have shown that increases in daily average outdoor RSP levels are associated with increased morbidity and mortality. There is new evidence that even shorter term exposures to RSP can have cardiopulmonary health effects, including SHS at the levels to which bartenders are exposed.[16–18] Lightweight, real-time battery-powered instruments, such as the active-mode MIE personalDataRAM (pDR-1200; Thermo Electron Corporation), have been developed, calibrated against standard pump-and-filter gravimetric methods,[42] and deployed in environmental epidemiology studies.[17] The personalDataRAM measures particle concentrations by light-scattering and incorporates a pulsed, near-infrared light emitting diode source, a silicon detector, an air pump, and a cyclone-filter to remove particles above a designated mass median aerodynamic diameter (MMD). The intensity of the light scattered forward by the airborne particles passing through the sensing chamber is linearly proportional to their concentration. There was a good correlation ($R^2 = 0.86$) between the pDR-1200 and gravimetric sampling in field studies of personal exposures to RSP in a European air pollution study.[17] The operating environment for the MIE pDR-1200 is from –10°C to 50°C, and from 10% to 95% Relative Humidity (non-condensing). In a recent performance evaluation of the pDR1200, the instrument precision was found to be 2.1%.[42]

The readings from the pDR 1200 can be affected by humidity, with overestimation of particle mass concentrations in the 2.5 μm MMD range ($PM_{2.5}$) by as much as 70% at relative humidity (RH) greater than 60%; at less than 60% RH, the overestimation averages about 25%.[42] A correction factor can be applied above 60% RH to adjust for humidity effects.[42] The MIE pDR's measured mass concentration is also affected by particle size, with overestimation of particle mass as much as 50% between about 0.7 to 1.2 μm MMD; however, the MIE pDR 1200 will underestimate particle distributions with MMDs in the size range of 0.2 to 0.5 μm by about 25%.[42] Cigarette smoke particulate matter (PM) is log-normally distributed liquid droplets, with a mass-median aerodynamic diameter of 0.23 micrometers (μm) (GSD 2.2 μm) when fresh, and 0.29 μm (GSD 1.4 μm), after ageing for 8 h.[41] For the particle size distribution characteristic of cigarette smoke and other combustion aerosols, the humidity and particle size effects oppose each other. Thus, it is necessary to calibrate the MIE on the aerosols to be measured.

PPAH

PPAH was chosen in part because it consists of a mixture of well-known carcinogens present in tobacco smoke, as well as diesel exhaust, and wood smoke.[19] PPAH have been implicated in heart disease and stroke mechanisms as well.[20] The classic PPAH compound is benz(α)pyrene, which is a known human lung carcinogen.[21] Total PAH include both gaseous and particulate phase compounds, and are thermally stable.[22] There are more than 100 PAH molecules; measurement of PPAH underestimates the total number of toxic PAH in the air. Portable real-time PAH monitors have been developed, calibrated against standard gas-chromatography /mass spectrometry methods, and deployed in environmental epidemiology studies.[13,21–25,44–46] A lightweight battery-powered data logging respirable PPAH monitor, the EcoChem PAS 2000CE, is deployed in these experiments. This monitor operates on the principle of photoelectric charging: airborne particles are drawn into a tube, illuminated with ultraviolet photons, and produce photo-electrons and positive ions which are collected by an alternating electric field, which is measured using a current amplifier. Only fine particles can be charged efficiently by this method, because electron recombination with the positive ions increases with particle size.

Photoelectric charging is surface-sensitive and therefore yields information on the surface concentrations of fine particles suspended in a gas. Particles from other than combustion sources generally cannot be charged photoelectrically due to the absence of PPAH. A linear relation between the photoelectric activity and the PPAH mass concentration in air has been determined.[40] The operating environment for the PAS 2000CE is 5°C to 40°C; the fraction of particle mass due to PPAH is independent of location and weather conditions. Outdoors, the major sources of PPAH particles are diesel exhaust and cars with defective catalytic converters.[22] PPAH particles are submicron in size, or "nanoparticles."

Monitor Calibration

The air quality monitoring equipment was calibrated in controlled experiments with smoldered Marlboro Medium 100's cigarettes as a source.[26] In the first calibration experiment (SiV3–10), RSP 3.5 μm in mass-median diameter ($PM_{3.5}$) were measured using a Thermo Anderson MIE pDR 1200 (with a factory-set calibration factor of 1.00), and a Kanomax 3511 Piezobalance (PZB). The PZB is a standard portable instrument, long used in field surveys of SHS RSP, and in controlled experiments involving human smokers.[11] The standard PZB must be read manually, and may be equipped with various impactors to collect different MMDs. However, recently, it has been modified to data-log to a computer,[47] in a series of experiments comparing the modified PZB with two colocated cyclone-equipped Stanford University mass-filters (CMFs), to obtain a gravimetric comparison sample (conditioned at a relative humidity of ~50% for a preweighing period of 5 h at a temperature of 20°C to 25°C). In several colocated measurement experiments, this modified PZB agreed with the CMFs to within ± 5%.[47] In the March 10th calibration experiment (Fig. 1), the PZB and the MIE 1200AN were set to measure 1-min average RSP ($PM_{3.5}$) concentrations from four Marlboro Medium 100s cigarettes smoldered together in a 41 m^3 bedroom, ventilated only by natural ventilation (air infiltrating into the room through cracks around the closed doors and windows). Sampling was initiated ~10 minutes after the cigarettes were extinguished to ensure a well-mixed environment; Figure 1 shows the total RSP (tobacco smoke + background) against time; the RSP decay curves showed parallel slopes for both instruments, with a decay rate from natural ventilation plus surface deposition $\Phi = 0.49$ air changes per hour (h^{-1}), but the MIE slope was displaced to somewhat higher concentrations (the effect of surface deposition of particulate SHS adds to the ventilation air exchange rate C_v, to yield the total effective air exchange rate, Φ). The initial readings of the PZB and the MIE are identical, with the PZB showing a more rapid decline for the first 10 minutes of decay, followed by a slope parallel to the MIE afterward. By contrast, the EcoChem PAS 2000CE (PAS) had a total removal rate $\Phi = 0.95\ h^{-1}$, nearly twice as high, likely due to a higher deposition rate.

In the experiment of Figure 1, the CMFs were run for 100 min, between 65 and 165 min. The CMF flow-rates measured a slightly smaller RSP size fraction, $PM_{2.2}$. The average MIE concentration was 19% higher than the PZB. In turn, the PBZ was 10% higher than the CMFs, which averaged 512.5 $\mu g/m^3$. The two CMF masses differed by 6%. The PAS was also run in parallel with the MIE for 245 min of decay time. The ratio of the average Marlboro Medium 100s decay mass concentrations, with their respective non-SHS backgrounds subtracted

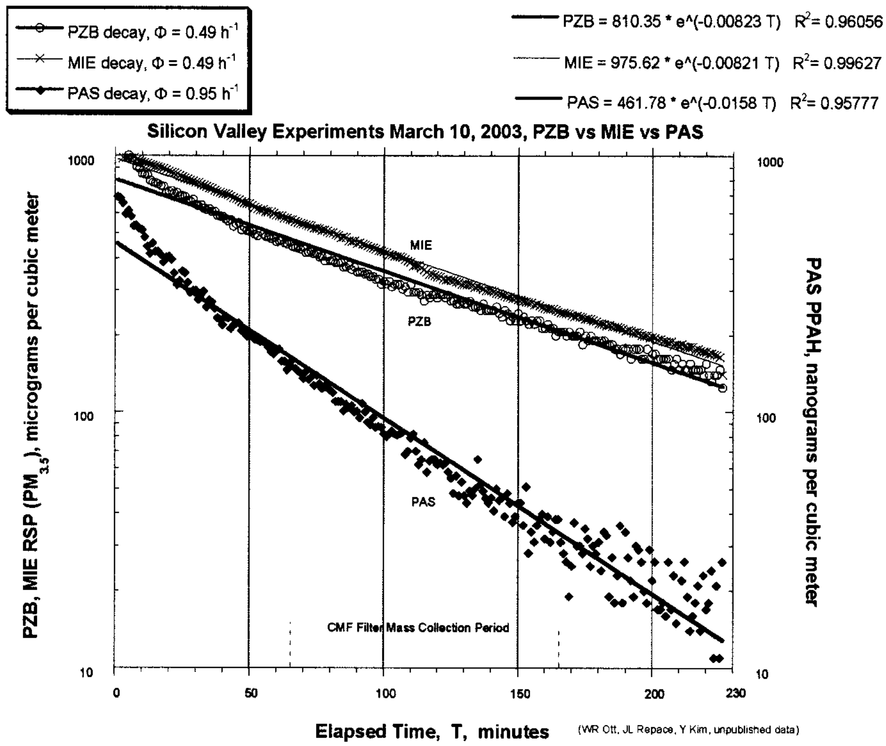

Fig. 1. One-minute-average total RSP ($PM_{3.5}$) data (tobacco smoke + background) versus time from a model 3511 piezobalance (PZB) versus a model MIE 1200AN nephelometer (MIE) versus a PAS2000 photo aerosol monitor measuring PPAH from the smoke of four Marlboro Medium 100s cigarettes smoldered in a 41-m^3 bedroom in a home; decay begins approximately 10 min after cigarettes are extinguished. The total RSP decay has the same regression slope for the MIE and PZB, $\Phi = 0.49$ air changes per hour (h^{-1}), whereas the PPAH decays at almost double the rate, at 0.95 h^{-1}. Φ is the effective air exchange rate, representing the sum of the removal rates by ventilation and surface deposition. A mass-filter (CMF) for $PM_{2.2}$, was run during the well-mixed period between 65 and 165 minutes. The relative humidity varied between 49% and 52%, and the temperature from 21°C to 23°C during the decay period.

(SHS-RSP/SHS-PPAH) was (478 $\mu g/m^3$/204 ng/m^3), which is, when expressed in the same units, a ratio of 2345:1.

To assess the potential impact of the size-cut differences between the CFMs and the other two RSP-measuring instruments, a second experiment was conducted. In the second experiment (SiV3–11, not shown), seven of the same Marlboro Medium 100s cigarettes were burned sequentially for 10 min every hour. Both the PZB and the MIE were reset to measure $PM_{2.5}$, a size closer to the CMF's $PM_{2.2}$. In the second experiment, the average particle concentration of MIE was 7% higher than the PZB readings (at an average relative humidity of 55%). The PZB averaged 9.6% higher than the average of the two CMFs, whereas CMFs differed by 0.3% from one another. The mass concentration of the RSP and the PPAH from all real-time instruments showed a repetitive characteristic[11] growth-and-decay "shark-fin" shape as (Fig. 2) cigarettes were ignited and extinguished, which attained a steady state oscillation pattern by the third cigarette (only the tail of the sixth and the entire seventh cigarette are shown). The second experiment showed that the total decay rate of PPAH (1.5 h^{-1}) was nearly twice that of RSP (0.8 h^{-1}) for both the PZB and the MIE, again suggesting that PPAH adsorbed faster than the total RSP on the room surfaces. Analysis of the data using a model[48] (solid curve in Fig. 2) indicates that the MIE data are consistent with a 13.6 mg RSP and the PZB with a 12.7 mg RSP emission per smoldered cigarette; the latter is about 90% of the ~14 mg RSP per cigarette emissions from airport lounge studies with human smokers.[49] In a fourth experiment (not shown), a human smoker smoked a Marlboro Lite 100 cigarette in a well-ventilated cruise ship stateroom to assess the PPAH emission from both exhaled mainstream and sidestream smoke using the PAS.[43] This cigarette emitted 14.9 μg of SHS PPAH per cigarette when smoked,[43] compared with 13.5 μg per cigarette measured by other workers.[37] In summary, the MIE concentration was 19% higher than the PZB in the first experiment (four Marlboros smoldered simultaneously), and 7% higher in the second experiment (seven Marlboros smoldered sequentially), while the PZB differed overall from the CMFs by ± 5% in several experiments. A further series of 8 experiments (VA) disclosed that the 95% confidence interval for two colocated Stanford CMFs was ± 6.2% (WR Ott, personal communication, July 12, 2004).

The discrepancy among the MIE, PZB, and CMF RSP readings is likely the result of the different physical principles of measurement. The MIE works on a light-scattering principle, and can yield different results when measuring different aerosols, which is why it must be calibrated for the specific aerosol to be measured. The PZB uses a vibrating quartz crystal whose frequency of vibration is slowed when mass is deposited electrostatically on the surface after passing through an particle-sizing impactor. The CMFs collect particle mass on a filter. Both the MIE and the CMF use particle-sizing cyclones. Both the PZB and the CMFs are aerosol-independent. Figure 1 appears to show a slight loss of mass for the PZB, possibly due to particle bouncing, as suggested by more rapid decline in slope relative to the MIE for the first 10 minutes. Although CMFs have been reported to lose water mass when measuring SHS,[51] the conditioning of the loaded filters for 5 hours at around

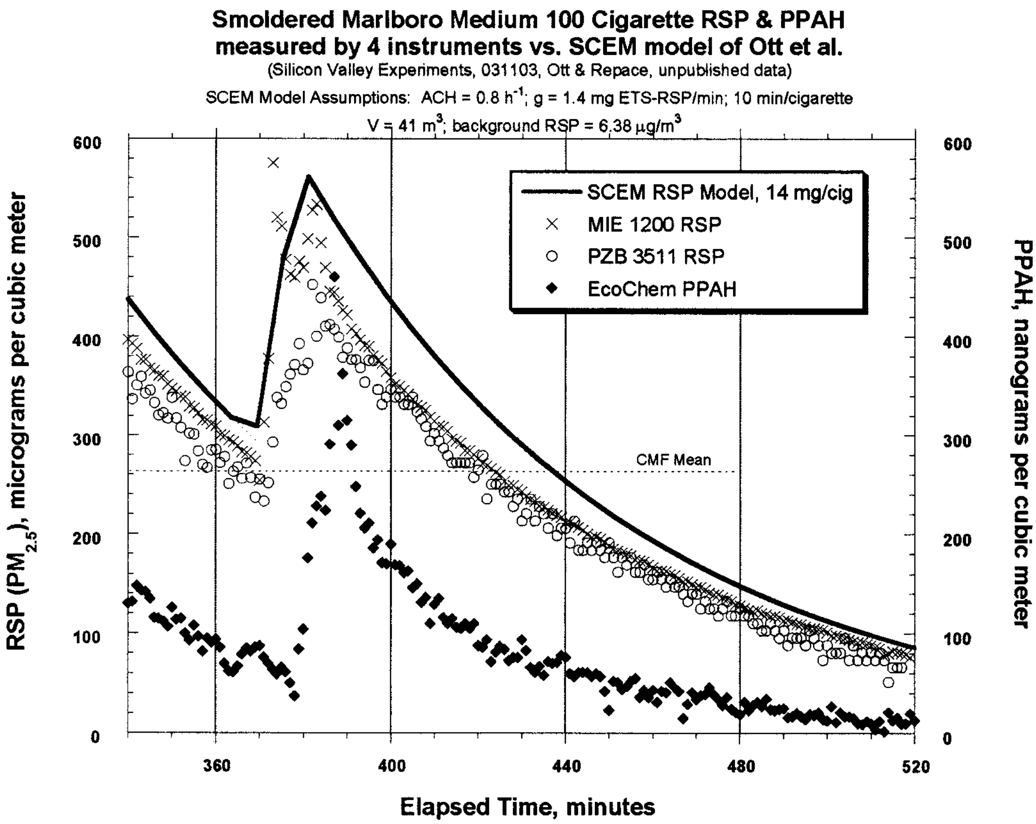

Fig. 2. One-minute-average total RSP ($PM_{2.5}$) measured by the PZB, the MIE, and the PAS for PPAH, for the decay of the sixth and growth and decay of the seventh (burning from 380 to 390 min) of seven Marlboros smoldered at the rate of 1 per hour, in a 41-m^3 bedroom. The seven-cigarette average for the CMF ($PM_{2.2}$), is shown (sample ends at 480 minutes, dotted line). $\Phi = 0.8\ h^{-1}$ on March 11, 2003. The RH was 54% and the temperature 22.5°C. Non-SHS background RSP and PPAH levels averaged 6.38 μg/m^3, and 2.5 ng/m^3, respectively.

50% RH prior to re-weighing should ensure that the samples have re-equilibrated with respect to aerosol water content (L. Hildemann, personal communication). I conclude that the active mode MIE reads no more than 10% to 20% higher than the PZB and the CMFs when measuring SHS RSP, and that within experimental error of the calibration experiments (eg, compare Figs. 1 and 2), there is no meaningful difference among the three instruments. I therefore report the MIE values unadjusted.

Part III: Field Measurements Made Prior to the Delaware Smoking Ban

In the Delaware field survey, the MIE pDR 1200 was used with a calibration factor of 1.00 and set to measure $PM_{3.5}$; the MIE was zeroed in HEPA-filtered air and the calibration rechecked prior to each day's sampling, and both were set to 1-minute averaging times. The EcoChem PAS was also used as factory calibrated. Both devices were synchronized via a laptop computer to time on a clock, which received timing signals from the NIST atomic clock in Boulder, CO. A quartz-crystal wristwatch, used to record each day's time-activity pattern, was also set to atomic clock time. In this manner, the electronically- and manually-recorded data could be correlated. The monitors were concealed in airline carry-on luggage, with intakes and exhausts connected to the environment through grommets by short lengths of Tygon tubing.

The air quality survey was conducted according to standard protocols for measuring SHS.[11,27,28] The air quality monitoring package was first deployed on Friday, November 15, 2002, prior to the Delaware hospitality industry smoking ban, making continuous measurements of RSP ($PM_{3.5}$) and PPAH from 6 P.M. to 12 A.M. Delaware weather on November 15, 2002 (6 P.M. to midnight) was fair and relatively mild, with barometric pressure between 30.01 inches of mercury and 30.06 inches of mercury. The outdoor temperature was 51.8°F at 6 P.M., decreasing to 44.6°F by midnight. Winds were 7 mph at 6 P.M., diminishing to 3.5 mph by midnight. Relative humidity outdoors ranged from 38% to 61% during the same hours (www.wunderground.com).

Eight hospitality venues in which smoking was occurring were visited, including a casino, six bars, and a pool hall/bar combination and data was recorded between venues for control purposes outdoors, in transit, and in a tenth-floor nonsmoking ho-

TABLE 2
Wilmington, Delaware, Indoor/Outdoor Air Quality Survey Results From November 15, 2002

Venue	Area (ft²)	Ceiling Height (ft)	Volume (m^3)	Ave. # Persons Present*	Ave. # Persons per 1000 ft²	Ave. # Burning Cigarettes*	% of Persons Actively Smoking*	Estimated Smoker Prevalence % of all Persons in Venue	Ave.* RSP, μg/m^3	Ave.* PAH, ng/m^3	D_s, Active Smoker Density†	C_v, Est.‡ Air Exchange Rate, Air Changes per Hour (h^{-1})
A. Casino central salon	32,499	14	12,884	176¶	-	15¶	8.5	25.5¶	205	163	-	-
B. Bar/ restaurant	1800	10	510	104	58	7.33	7.0	21	337	241	1.44	2.9
C. Bar/ restaurant	16,740	33	15,573	24.3§	-	3	12.3§	37§	44	44	0.02	0.30
D. Bar/ restaurant	5175	30	4396	75.5	15	2.33	3.1	9.3	96	46	0.05	0.38
E. Bar/ restaurant	2592	10	710	135	52	2	1.5	4.5	127	89	0.28	1.6
F. Bar/ restaurant	2228	8	518	102	46	1	1.0	3.0	103	53	0.19	1.34
G. Taproom	864	12	294§	170§	197	2.5	1.5	4.5	252	183	0.85	2.3††
H. Pool hall	3780	10	1070	191	51	9.7	5.1	15.3	686	249	0.90	0.87
Mean (SD) All Venues					**70 (SD 64)**		**5.0 (SD4.0)**	**15.0 (SD12.0)**	**231 (SD 207)**	**134 (SD 86.5)**	-	**1.4 (SD0.97)**
Nonsmoking hotel room 1004	~150	8	34	1	-	0	0	0	**8.0 (SD 1.0)**	**15 (SD 7.4)**	0	-
Outdoors/ In transit**	-	-	-	0	-	0	0	0	**11 (SD 3.2)**	**27 (SD 28)**	0	-

*29 min avg, SD 8 min.
†D_s in units of burning cigarettes per 100 m^3.
‡Using Eq. 1.
§Bar area only.
¶Persons at peripheral slots in central salon only.
||66-min weighted average (45 min before and 21 min after all venue sampling).
**Mean of 5 to 25 min samples; see Figure 3.
††Outer door open.

tel room at a Wilmington hotel prior to and after field sampling. Each venue was visited for an average of approximately 1/2 hour (range, 15 to 45 min). All venues were well-patronized during the measurements. The monitoring package was deployed as an area monitor rather than a personal monitor, and as such was generally unobtrusively located along an outside wall 2 ft to 4 ft from the floor, for the bars and the pool hall areas; in the casino, which had more open space, the package was moved about the 1000-foot perimeter of the main salon during the measuring period.

Each room's dimensions were measured using a Calculated Industries (Carson City, NV) Dimension Master ultrasonic digital ruler (range 2 to 50 ft, resolution ± 1%), by a Bushnell (Lenexa, KS) Yardage Pro Sport Compact infrared laser Rangefinder (range 10 to 700 yd, resolution ± 1 yd), or in the case of Bar G, estimated by pacing off. Except for the multiroom casino, where only a representative sample was taken from the main salon, the total number of persons present was counted at the beginning and end of the sampling period, and the number of burning cigarettes being smoked was counted at the beginning, middle, and end of that period. The clock time upon entering and departing each venue was recorded so that it could be identified in the data. Personnel from American Lung Association of Delaware designated the venues to be sampled, provided transportation, and assisted the principal investigator with person-counts.

Table 2 organizes the study measurements and results. Figure 3 shows a "time series" plot of the data: the RSP and PPAH concentrations as a function of time. The heavy pollution in the hospitality venues relative to outdoors is evident. Figure 4 displays the RSP and PPAH concentrations as a function of smoker density D_s and air exchange rate C_v. Both RSP and PPAH

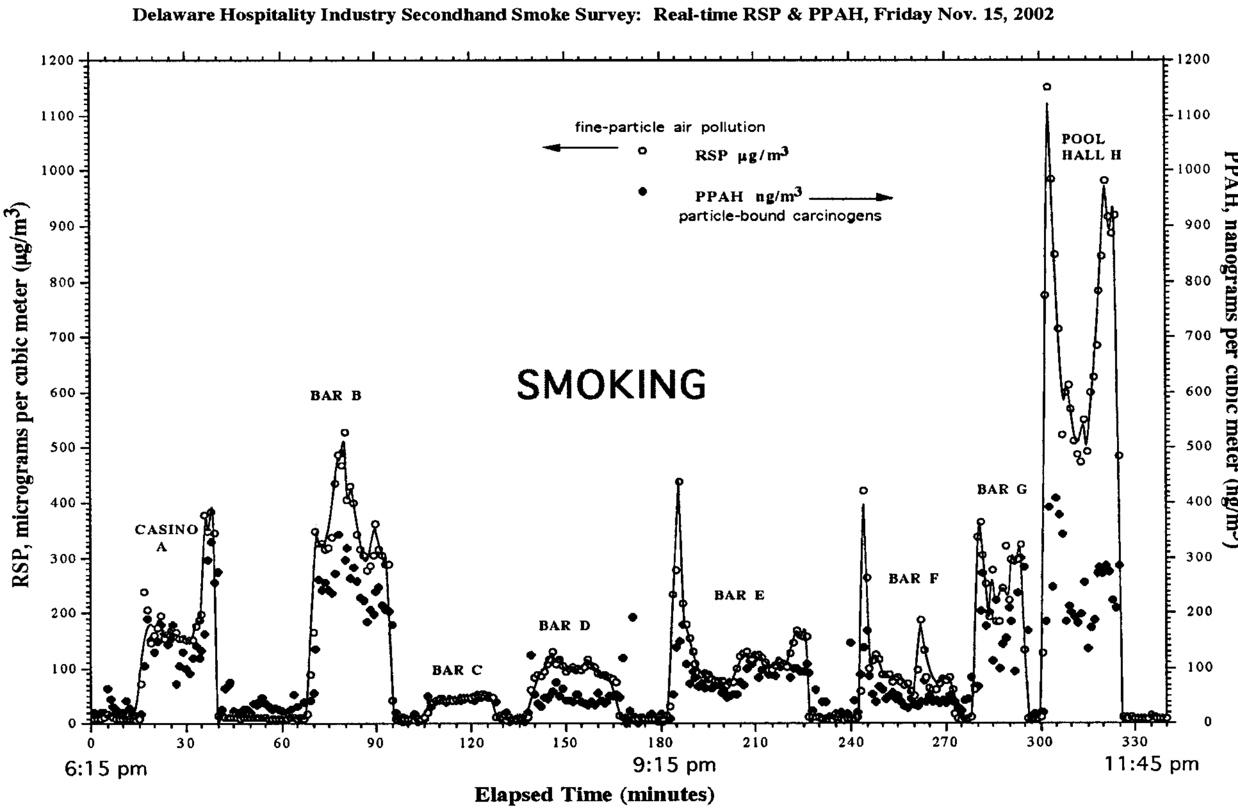

Fig. 3. Real-time RSP air pollution and airborne carcinogens (PPAH) in a casino, six bars, and pool hall before a smoking ban. Data recorded on Friday Evening, November 15, 2002. Outdoor and in-transit location measurements precede & follow each Venue sampled. For comparison, the National Ambient Air Quality Standard for fine-particle air pollution ($PM_{2.5}$) is 15 $\mu g/m^3$, annual average. All venues were crowded, with persons observed to be smoking throughout the sampling periods.

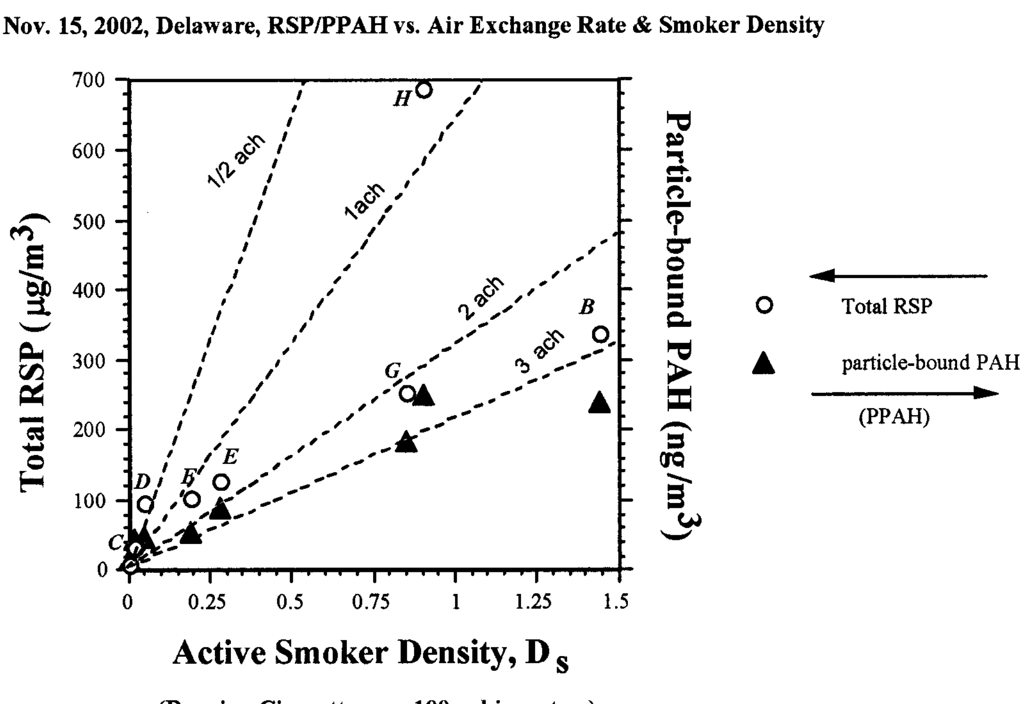

Fig. 4. Air pollution in seven of eight hospitality venues (casino A not shown) in which smoking occurred and a nonsmoking hotel room in Delaware on Friday evening November 15, 2002. RSP and PPAH values are plotted versus Ds and Model-estimated ventilation air exchange rates, C_v, for RSP, using Equation 1. Both RSP and PPAH increase with increasing D_s. C_v (dashed lines) for the seven venues ranges from approximately 0.4 to 3 air changes per hour (ach).

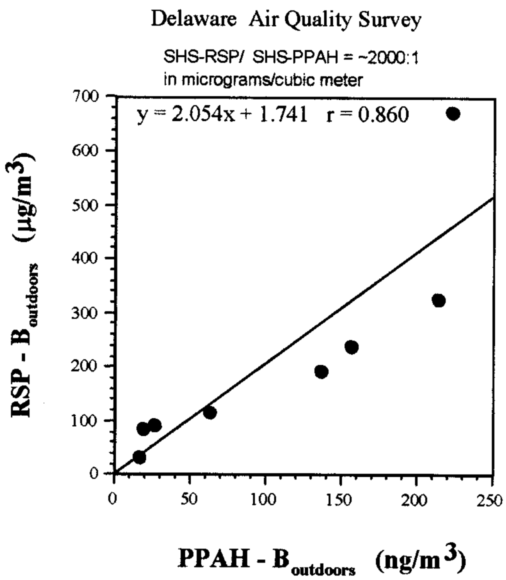

Fig. 5. A plot of total indoor RSP minus the average outdoor/hotel RSP background (estimated SHS − RSP) versus total indoor PPAH minus the average outdoor/hotel PPAH background (estimated SHS − PPAH) presmoking ban for the eight hospitality venues on November 15, 2002. A strong linear correlation between SHS − RSP and SHS − PPAH is seen (r^2 = 0.74), with a RSP/PPAH ratio of ~2000:1.

concentrations increase with increasing smoker density. A regression of RSP against D_s (not shown) yields an $r^2 = 0.54$, showing that 54% of the variance is explained by D_s; model-estimated air exchange rates C_v (dashed lines) appear to explain the remainder of the variation; a regression for PPAH against D_s (not shown) yields $r^2 = 91$, suggesting that high constant rates of surface deposition dominate PPAH removal at low air exchange rates (compare RSP to PPAH decay in Fig. 1 and after the last cigarette is out in Fig. 2). High rates of surface deposition also suggest heavy surface contamination by carcinogenic PPAH in smoking venues. Figure 5 shows that a strong correlation exists between the RSP and PPAH ($r^2 = 0.74$). Figure 5 suggests that the average SHS-RSP/SHS-PPAH ratio is about 2054:1. This is within about 12% of the 2345:1 ratio measured in the controlled experiment described above.

Average Venue RSP Concentrations

The RSP levels in seven of eight venues met or exceeded predicted levels based on default assumptions. It appears that smoking indoors generally raised the short-term levels of fine particle air pollution massively compared to the smoke-free condition. The combined average of the mean outdoor measurements and the hotel room for RSP was 9.5 micrograms per cubic meter (μg/m^3). By comparison, the average taken over all indoor hospitality venues was RSP, 231 μg/m^3 (SD 208 μg/m^3), nearly 25 times background, with a median value of 115 μg/m^3 (not shown). Relative to background levels, assuming the indoor RSP consists of SHS plus outdoor background, it appears that SHS contributed an average of (230 –9.5)/230 = 96% of the RSP pollution.

Average Venue Smoking Prevalence

Table 2 shows that most venues had average-to-very low smoking prevalence. The average prevalence of active smoking (burning cigarettes) for all venues was 5% of observed patrons, corresponding to an estimated habitual smoker prevalence of 15%. This is two thirds of the 23% smoking prevalence of the adult population in Delaware. Only two of the eight venues had an estimated smoking prevalence as high or higher than 23%, the Casino, and Bar C; however, the bar area in the latter was only a small fraction of the total area, which had a well-attended restaurant and a large arcade game area populated with uncounted nonsmoking persons. The remainder of the venues had smoking prevalences ranging from one eighth to one half of the average state prevalence. The measured RSP levels in this study are comparable to those in an earlier study which measured RSP (MMD $PM_{3.5}$) using a PZB in 19 venues in the Washington, DC metro area in 1978, which averaged 311 μg/m^3 (SD 255 μg/m^3), nine times background, with a median value of 239 μg/m^3.[11] (In the 1978 study, 8.6% of persons were actively smoking, when the US smoking prevalence was 33%.)

Average Venue Compliance With the NAAQS

The average taken over all eight venues violated the NAAQS for respirable particulate air pollution. Overall, the average RSP level for all venues *de facto* violated the NAAQS by a factor of greater than 4 {[(1/3)(231 μg/m^3)(250 days/y)/365 days + (16.6 μg/m^3)(365 days/y)/365 days]/15 μg/m^3 = [53 + 16.6]/15 = 4.6}. Assuming these levels are typical, this is a significant increase in the risk of respiratory disease for all hospitality workers.

Average Venue PPAH Levels

For PPAH, the average of the mean values for all eight venues was 134 ng/m^3, nearly seven times the average of the hotel room and outdoor background of 21 ng/m^3. Relative to background levels, assuming the indoor PPAH consists of SHS plus outdoor background, it appears that SHS contributed an average of (134 –21)/134 = 84% of the PPAH pollution. Although no standards have been set for PPAH, on a 24-h average basis for the 8 venues sampled, PPAH exceeded background levels by a factor of [(113/3) + 21)]/21 = 2.8, significantly increasing exposure of workers to substances known to be implicated in the causation of cancer, heart disease, and stroke.

Average Venue Air Exchange Rate

The average model-estimated ventilation air change rate (excluding the casino, where the total floor area was not measured) was 1.4 air changes per hour, much lower than the 18 air changes per hour derived for bars from the default assumptions of ASHRAE Standard 62. All venues either significantly or massively failed to meet the recommended ventilation rates of ASHRAE Standard 62, which are generally incorporated into local building codes. Although the casino ventilation rate could not be assessed based on the data collected, comparison of the measured concentration (205 $\mu g/m^3$) with that predicted (118 $\mu g/m^3$) suggests that the ventilation rate was about half that recommended by Standard 62, since the smoking prevalence was the same as predicted, the occupancy was fairly full, but the concentration was about double that predicted. Table 2 shows that for the seven venues for which air exchange rates could be calculated from the measured data, none had ventilation rates more than one sixth as high as ASHRAE recommends. How could this occur? Supplying fresh conditioned air imposes typical costs of the order of $1 per square foot per year at ASHRAE-recommended supply-air rates; thus, there is an economic incentive for building owners to under-ventilate buildings by increasing the amount of recirculated air. This incentive, coupled with a lack of enforcement of operational code-specified ventilation rates by local authorities—a common failure throughout North America—leads to widespread noncompliance. Although ASHRAE design ventilation rates are incorporated into many regional building codes, once the air-handling system is installed and inspected, compliance with these recommended ventilation rates is not enforced, perhaps because it is difficult and costly to measure ventilation rates as well as to train and deploy personnel to enforce them in thousands of buildings.

Part IV: Field Measurements Made After the Delaware Smoking Ban

Because RSP can be generated by cooking sources,[52] it was desirable to repeat the air quality survey in the absence of smoking during typical hours of operation. All hospitality venues were re-measured after the smoking ban took effect, and it was judged by Coalition personnel that the eight venues' compliance with the ban was satisfactory. On Friday evening, January 24, 2003, approximately 2 months after the statewide hospitality industry smoking ban, the study described in Part III was repeated, with RSP and PPAH measurements made from 6 P.M. to 12 A.M., in the same casino, six bars, and pool hall as prior to the ban, in the same order, and about the same time of night. As in the field study before the ban, control measurements were performed outdoors, in transit, and in the same tenth-floor non-smoking room at a Wilmington hotel. Table 3 organizes the study results. The number of persons present in the eight premises are of the same order as before the ban, with some premises showing more persons, and some less. Real-time miniaturized data logging environmental monitoring equipment for temperature, relative humidity, carbon monoxide, and carbon dioxide (Models L76, T15, T16, Langan Products, San Francisco, CA), unavailable to the investigator at the time of the preban field study, was also deployed. The Langan data logger was programmed to read at 1-min intervals and was synchronized by computer with the RSP and PPAH monitors. Carbon dioxide measurements are useful for estimating the ventilation rate per occupant, for comparison with ASHRAE Standard 62.

Wilmington weather (6 P.M. to Midnight) was fair and cold, with barometric pressure between 30.27 inches of mercury to 30.33 inches of mercury. The outdoor temperature was 26.6°F at 6 P.M., decreasing to 21.2°F by midnight. Winds were 20 mph at 6 P.M., and lowered to 8.1 mph by midnight. Relative humidity ranged from 31% to 54% during the same period (www.wunderground.com). However, temperature in an outside pouch of the monitoring package, where the environmental monitor was located, varied only between 21°C and 23°C, while relative humidity varied between 48% and 53%.

Measurement of Carbon Dioxide (CO_2) Levels as A Surrogate for Air Exchange Rate

Appendix C of ASHRAE Standard 62–1999[29] specifies the following equation for C_s, the equilibrium CO_2 levels in parts per million (ppm) in a space:

$$C_s = \frac{N}{V_o} + C_o \qquad (2)$$

where N is the CO_2 generation rate per person (N = 0.30 L/min, corresponding to office work), V_o is the outdoor airflow rate per person, and C_o is the CO_2 concentration (ppm) in the outdoor air; $C_o \sim 400$ ppm, and N = 5000 ppm-L/s-occupant. Equation 2 is typically used to estimate the flow rate adequacy based upon an indoor CO_2 measurement. Note that the flow rate of V_o = 30 CFM/person (15 L/s-p) specified by ASHRAE 62–1989 for gambling casinos or bars permitting smoking corresponds to a CO_2 level of C_s = (5000/15) + 400 = 733 ppm.

TABLE 3
Wilmington, Delaware, Postsmoking Ban Indoor/Outdoor Air Quality Survey From January 24, 2003

Venue	Ave. # Persons on Entire Premises	Ave. Carbon Dioxide (CO_2) ppm	~Temp. °F	Relative Humidity Range %	Persons per 1000 ft^2	Avg.* RSP, µg/m^3	Percent of Preban RSP Value	Avg.* PPAH, ng/m^3	Percent of Preban PPAH Value	Estimated† Ventilation rate L/s-P from CO_2	Estimated† Air Exchange rate, h^{-1} from CO_2
A. Casino (entire)	825[c]	820	68	6–14	-	9.4	4.6	3.7	2.3	11.9	-
B. Bar/ restaurant	188	1716	63	10–23	104	24	7.0	1.3	0.5	3.8	5.0
C. Bar/ restaurant	218§	784	63	12–20	13	8.4	25	3.4	7.8	13.0	0.66
D. Bar/ restaurant	137	861	61	12–27	26	4.6	4.8	2.6	5.6	10.8	1.2
E. Bar/ restaurant	88	1302	59	14–22	34	7.4	5.8	9.8¶	11	5.5	2.5
F. Bar/ restaurant	113	775	59	16–25	51	2.5	2.5	1.7	3.2	13.3	10.7‖
G. Taproom	188	940	59	17–21	217	21	8.3	11¶	6.0	9.3	21‖
H. Pool hall	117	2000	57	17–34	31	119	17	3.0	1.2	3.1	1.2
Mean All Venues	-	-	-	-	-	-	**9.4**	-	**4.7**	-	-
Nonsmoking hotel room** 1004	1					2.0 (SD 1.9)	-	3 (SD 1.9)	-		-
Outdoors/In Transit††						7.4 (SD 8.9)		7.9 (SD 11.5)			-

Carbon monoxide level, ppm: A, 2.0; B, 2.5; C, 2.5; D, 2.2; E, 2.8; F, 2.2; G, 2.3; H, 3.0.
*30 min (SD 11 min) averages.
†Using Eq. 2.
‡Persons around peripheral slots = 196.
§33 persons in bar area.
¶Smokers outside door.
‖~6' from front door.
**51 min average (28 min before and 23 min after all Venue sampling).
††7- to 35-min samples.

Estimation of Air Exchange Rates From CO_2 Levels

At ASHRAE Standard 62 default (maximum) occupancy, a CO_2 level of 733 ppm indicates an air exchange rate of 18 air changes per hour (h^{-1}). However, if equilibrium is not achieved or the bar occupancy is less than maximum, 733 ppm will represent less than 18 h^{-1}. For example, Venue *C* has a CO_2 level of 784 ppm. This calculates out to 13 L per second per person (L/s-P) in comparison with a specified 15 L/s-P from the ASHRAE Standard. But Venue *C* also has a very low occupancy of 13 persons per 1000 ft^2, coupled with a very high 33 ft ceiling. The corresponding air exchange rate calculates out to be just 1/27th of 18 air changes per hour [(218 P/15,573 m^3)(13.0 L/s-P)(3.6 m^3-s/L-h) = 0.66 h^{-1}]. However, it is close to the air exchange rate of 0.36 hours^{-1} calculated from the SHS RSP concentration using the Habitual Smoker Model of Equation 1. The rightmost column of Table 3 shows the air changes per hour calculated for each venue from the CO_2 levels (except for the casino, whose volume was not determined). Although Venue C's ventilation rate per occupant is second best of the seven venues, and is 87% of the design CO_2 level, the actual rate of air exchange –which determines the rate of pollutant removal –is totally inadequate.

Venues *F* and *G* appear to have higher air exchange rates than the other venues, this appears to be an artifact of having located the monitoring package too close to the front doors through which persons were constantly coming and going; also, sampling was performed on a night when there was a substantial indoor/outdoor temperature difference, leading to considerable influx of cold air from outdoors, causing dilution of the localized CO_2 levels.

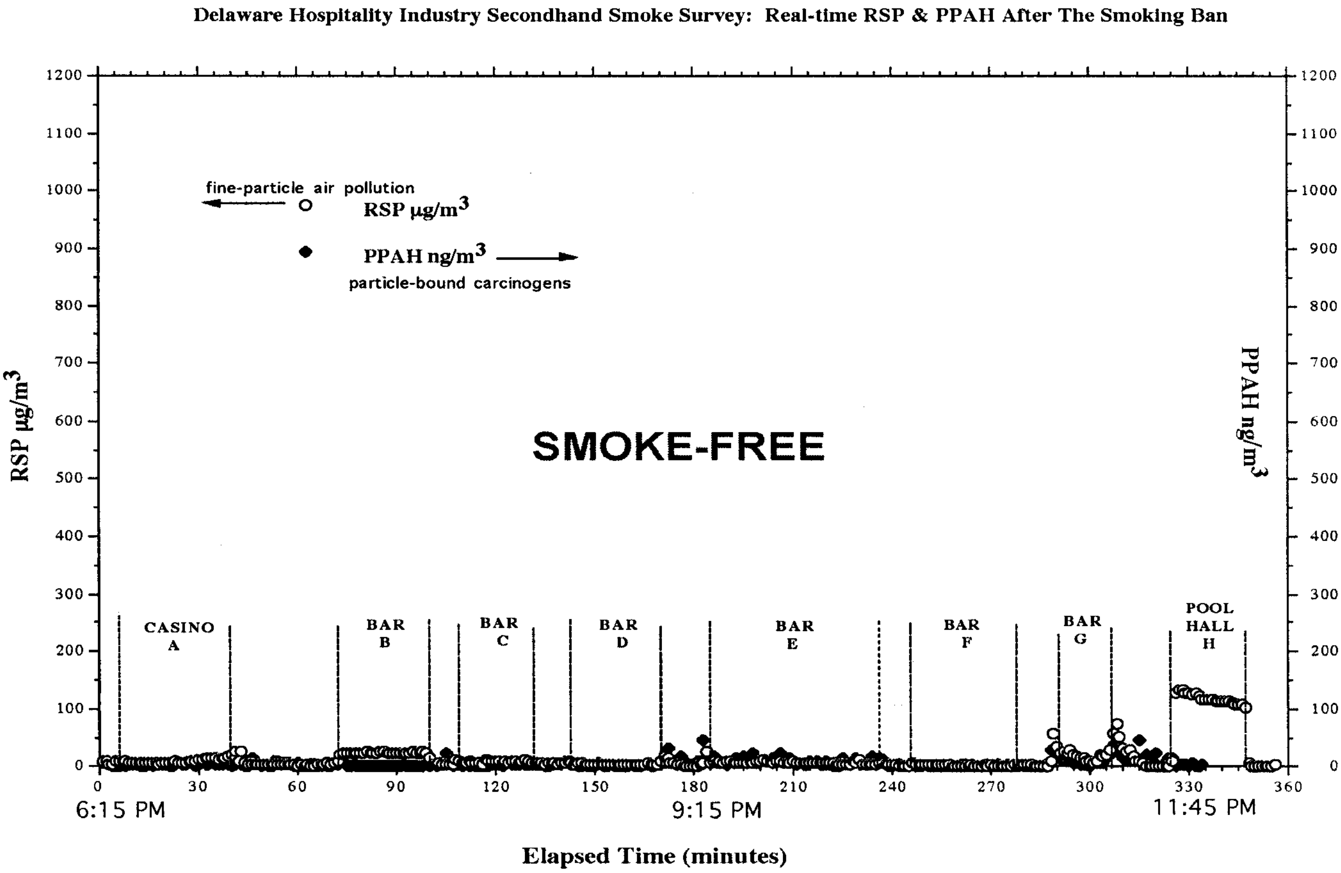

Fig. 6. Real-time RSP air pollution and airborne carcinogens (PPAH) in the casino, six bars, and the pool hall after the smoking ban. Compare with Fig. 3. Data recorded on Friday Evening, January 24, 2003. Outdoor and in-transit location measurements precede and follow each venue sampled. All venues were crowded, and all appeared to be in compliance with the Delaware smoking ban.

Postsmoking Ban RSP and PPAH Concentrations

Figure 6 shows the RSP and PPAH concentrations as a function of time; the dramatic improvement in air quality in all venues relative to conditions before the smoking ban is evident by contrasting Fig. 6 with Fig. 3. Except for the pool hall, most venues are indistinguishable from background concentrations. Even the very poorly ventilated pool hall (measured CO_2 level 2000 ppm, despite its lower than default occupancy, compared to the 733 ppm predicted for an ASHRAE-compliant venue) has only 17% of preban RSP (possibly caused by chalk dust) and just 1.2% of pre ban PPAH. The RSP air quality in most of these 8 venues is now little different from outdoors. PPAH is very close to or below outdoor background levels in all venues.

Comparison of preban and postban RSP and PPAH in Table 3 shows that the levels of each in the absence of indoor smoking are small fractions of those measured during smoking, demonstrating conclusively that it is tobacco smoke—not confounders from cooking or other sources—that produced the massive fine particle and carcinogen pollution observed in Fig. 2. Postban levels of RSP ranged from 2.5% to 25% of preban values and averaged 9.4%, whereas postban PPAH concentrations ranged from 0.5% to 11% of preban levels and averaged 4.7%. Thus, the postban measurements suggest that approximately 90% of the fine particle pollution and 95% of the particle-bound PAH carcinogens can be attributed to tobacco smoke. This may be contrasted with the preban results using the outdoor background as a reference point, suggesting that, during smoking, for the 8 hospitality venues overall, an estimated average of 96% of the RSP concentration and 84% of the PPAH concentration was caused by SHS. Expressing these as a range, it appears that 90% to 95% the RSP pollution, and 85% to 95% of the PPAH pollution measured in the preban visit was caused by smoking. The smoking ban has generally reduced the exposure of workers and patrons to these harmful pollutants to outdoor background levels, except for RSP in the pool hall, which still has been reduced to a fraction of its preban concentration. Table 2 shows that Venue *C* had an average of only three burning cigarettes during the November 15th visit. Table 3 shows for Venue *C*, that this was sufficient to increase the carcinogenic PPAH concentration in this massive 550,000 cubic foot facility by (1/

7.8%) = 13-fold. Even huge dilution volumes cannot overcome the high emission rates of toxic and carcinogenic pollutants generated during cigarette smoking.

Discussion

Physical Interpretation

SHS causes the massive preban RSP and PPAH pollution elevations shown in the 8 hospitality venues, as Figs. 1 through 6 demonstrate conclusively: Figures 1 and 2 demonstrate that the RSP monitors used in the study are consistent with the measurements of standard monitors used to detect SHS RSP. Figure 2 shows that the SHS PPAH and RSP track both each other and cigarette ignition and extinction, following expected physical relationships and cigarette emissions for SHS. The controlled quality-assurance experiments showed that SHS is capable of generating RSP and PPAH concentrations massively above background. Figure 3 shows that in the presence of smoking in the field, both RSP and PPAH are elevated far beyond outdoor background levels, with increases in average levels of RSP and PPAH exposure by ten- to twenty-fold. These observed increases are consistent with model predictions: assuming the 9.5 $\mu g/m^3$ preban RSP background of Table 2, The predicted RSP level from SHS of 98 $\mu g/m^3$ for an ASHRAE default bar is ten times background, and using the 4.7 $\mu g/m^3$ postban RSP background of Table 3, is 20 times background. Figures 4 and 5 show respectively that in the field, both RSP and PPAH increase strongly with smoker density and correlate highly with each other. Figure 6 shows that after smoking has been banned, indoor and outdoor RSP and PPAH levels are virtually indistinguishable, which is consistent with Fig. 4.

The controlled experiments showed a (SHS-RSP/SHS-PPAH) ratio of 2345:1 for a single brand of the most popular cigarette, compared to a 2054:1 ratio for multiple brands smoked in the field study. This suggests that the SHS-PPAH concentration may be predicted by dividing the constant in Equation 1 by a factor of 2000. For the six bars measured in this study, measured RSP concentrations averaged 109 $\mu g/m^3$ (SD of the means: 83 $\mu g/m^3$) compared with 115 $\mu g/m^3$ predicted for the typical Delaware pub using the Habitual Smoker Model, with mean outdoor $PM_{2.5}$ from State air quality monitoring network data added. Thus, observations agree with predictions. This agreement shows the value of modeling based on ASHRAE default assumptions. The controlled experiments plus the model results generalize the study's results.

Health Implications

What are the potential health consequences of such SHS pollution levels shown in this study? According to the Agency for Toxic Substances and Disease Registry,[33] "animal studies have shown that PAH exposure increased the rate of birth defects in test animals, and reduced their ability to fight disease, even after short-term exposure. It is not known whether these effects occur in people. However, people exposed to PAHs for prolonged periods have developed cancer. Animal studies have demonstrated that some PAHs have caused lung cancer, stomach cancer, and skin cancer." Ten carcinogenic particulate-phase PAHs have been identified in tobacco smoke as listed in Table 4; this is one-sixth of all known tobacco smoke carcinogens.[35,52]

To place the preban Wilmington PPAH results into perspective, they can be compared with measurements made using the EcoChem PAS2000 on outdoor levels of PPAH measured in nine sites in Roxbury, a Boston city neighborhood chosen to represent a range of traffic densities polluted by heavy diesel bus and truck traffic emissions. Median Roxbury concentrations ranged from 4 to 57 ng per cubic meter (ng/m^3), and averaged 18 ng/m^3 over all sites.[44] Similar measurements were also made using the EcoChem PAS2000 at the Baltimore, Maryland, Harbor Tunnel tollbooth for 24-h periods during a 3-day period in June 2001.[45] The 3-hour PPAH tollbooth medians ranged from 9.3 ng/m^3 (late evening) to 199 ng/m^3 (early morning rush).[45] By contrast, the medians (not shown) for the eight Wilmington Venues in this study ranged from 43 ng/m^3 to 234 ng/m^3 (close to the means of Table 2). In Fig. 3, the outdoor PPAH levels in this study, before and after the visit to Casino A, were measured on Interstate Highway I-95 in Wilmington during rush hour, but were considerably lower than in the Casino. Figure 6 confirms these results. In other words, the PPAH levels from tobacco smoking in the Wilmington hospitality venues were higher than those from heavy truck, bus, and auto traffic on the main interstate highway (I-95) on the East Coast of the United States during rush hour or in a heavily trafficked neighborhood in Boston.

A body of evidence connecting exposure to SHS to premature death has accumulated during the past two decades, and has been summarized in several authoritative reports compiled by panels of scientific and medical experts. SHS is a known human carcinogen, a classification which includes asbestos, coal tar dyes, and mustard gas.[1] Thus, the reduction in carcinogenic PAHs caused by the Delaware smoking ban as shown by this study, has demonstrably reduced the risk of cancer for thousands of Delaware hospitality workers, managers, and patrons.

Similarly, the preban Wilmington hospitality industry RSP levels, whose means ranged from 44 $\mu g/m^3$ to 686 $\mu g/m^3$ and averaging 230 $\mu g/m^3$ over all sites (medians 44 $\mu g/m^3$ to 626 $\mu g/m^3$ and averaging 137 $\mu g/m^3$ over all sites; data not shown), can be unfavorably compared to heavy outdoor RSP pollution. Typical median outdoor levels of $PM_{2.5}$ during a 2-month period in

TABLE 4
Carcinogenic PPAH, IARC Status, Amount in Cigarette Smoke

Particulate Phase PAH (PPAH)	IARC Carcinogen in Laboratory Animals	IARC Carcinogen in Humans	Amount Measured in SHS (ng/cig)*	References
Benz(α)anthracene	Sufficient		412	16,35
Benzo(b)fluoranthene	Sufficient		132	16,35
Benzo(j)fluoranthene	Sufficient		32	16,35
Benzo(k)fluoranthene	Sufficient			35
Benz(α)pyrene	Sufficient	Sufficient	74	16,35
Dibenzo(a,i)pyrene	Sufficient			35
Dibenz(a,h)anthracene	Sufficient			35
Dibenzo(a,l)pyrene	Sufficient			35
Indeno(1,2,3-cd)pyrene	Sufficient			35
5-methylchrysene	Sufficient			35
All PPAH in SHS†			1067	16
All PPAH in SHS‡			13,500	37
All PPAH in SHS‡			14,850	§
Inhaled dose of PPAH to a cigarette smoker			200	38

*ng/cig = nanograms per cigarette. Blank cells indicate no data available.
†Machine-smoked 1R4F research cigarette.
‡Sidestream plus exhaled mainstream smoke from a human smoker.
§Repace JL. Indoor and outdoor carcinogen pollution on a cruise ship in the presence and absence of tobacco smoking (submitted for publication).
IARC, International Agency for Research on Cancer.

2001 at the same nine sites in the heavily polluted Roxbury neighborhood study described above, varied from 12 $\mu g/m^3$ to 86 $\mu g/m^3$, and averaging 52 $\mu g/m^3$ over all sites.[44] This is also similar to the I-95 RSP levels before and after the site visit to the Casino (Figs. 2 and 6), and agrees with earlier findings in the Washington DC area.[11] Thus, preban Wilmington hospitality RSP medians averaged (137/52) 2.6 times higher than on I-95 in Delaware and on Boston City streets heavily polluted with diesel trucks and buses.

Concerning RSP air pollution, Samet et al.[36] concluded that there is consistent evidence that elevated levels of fine particulate matter in the air are quantitatively associated with the risk of death from all causes and from cardiovascular and respiratory illnesses. Other indicators of impaired respiratory health, such as upper and lower respiratory symptoms, and decrements in lung function also occur with increasing particulate air pollution. Exposure to SHS has been linked to both cardiovascular and respiratory disease mortality.[3] Long-term repeated exposure to high particulate air pollution, like that experienced by workers in the hospitality industry, is known to increase the risk of chronic respiratory disease and the risk of cardiorespiratory mortality. Nationally, only 13% of bartenders worked in workplaces with smoke-free policies in 1999.[43] Short-term exposures to particulate air pollution, like that experienced by hospitality industry patrons, can aggravate existing cardiovascular and pulmonary disease and increase the number of persons in a population who become symptomatic, require medical attention, or die.[16] Thus, it may be confidently stated that the smoking ban in the Delaware hospitality industry has decreased the risk of these diseases in both workers and patrons, as the levels of fine particle air pollution in these venues has decreased by ten to twenty fold.

Finally, according to the Delaware Behavioral Risk Factor Survey, the prevalence of cigarette smoking among Delaware adults declined by 11% in 2003, and smoking among young adults (aged 18 to 24) decreased by a quarter, from 36% in 2002 to 27% in 2003. Delaware's governor attributed this decline to Delaware's Clean Indoor Air Act.[53] Thus, Delaware's Clean Indoor Air Act has an unintended beneficial side-effect: it saves smokers' lives as well as nonsmokers' lives.

Summary

Using state-of-the-art monitoring equipment calibrated on SHS in quality assurance studies, air quality was assessed in eight hospitality venues in Delaware. A casino, six bars, and a pool hall were sampled on Friday evening, November 15, 2002, under conditions of unrestricted smoking, and again on Friday evening, January 24, 2003, 2 months after a smoking ban. Measurements were made of RSP and PPAH, two pollutants known to increase risk of respiratory disease, cancer, heart disease, and stroke. Before the smoking ban, all venues were heavily polluted, with indoor RSP levels averaging 20 times outdoor background. For workers, these levels violated the annual NAAQS for fine particles ($PM_{2.5}$) by a factor of 4.6. Wilmington hospitality workers were exposed to RSP levels 2.6 times higher than on Boston City streets heavily polluted by truck and bus traffic. Wilmington preban indoor carcinogenic PPAH averaged 5 times higher than outdoor background levels, tripling workers' daily PPAH exposure, and exceeding those measured at a tollbooth on one of the major US interstate highways.

By contrast, subsequent to the smoking ban, the indoor air quality levels for both pollutants were, except for RSP in one venue, indistinguishable from outdoors. SHS contributed 90% to 95% of the RSP air pollution during smoking, and 85% to 95% of the carcinogenic PPAH. This occurred despite a smoking prevalence averaging 15%, much lower than the Delaware average of 23%. Hospitality industry air quality was likely worse in rural parts of the State where smoking prevalence is higher. Estimated outdoor air exchange rates were very low, apparent casualties of economic pressures in the hospitality industry coupled with the lack of regulation. However, increasing ventilation or air cleaning to satisfy the NAAQS during smoking would require an impractical 80 air changes per hour if the outdoor air were 60% cleaner than it actually is. At the actual 16.6 $\mu g/m^3$ $PM_{2.5}$ level for New Castle County, the NAAQS could not be achieved without cleaning the outdoor air supply. Nevertheless, even if all these measures were taken, SHS would still pose a carcinogenic and toxic risk to be dealt with.[54,55] This air quality survey demonstrates conclusively that the health of Delaware hospitality workers and patrons has been endangered by SHS pollution. The Delaware Clean Indoor Air Act's ban on smoking in hospitality workplaces eliminates that hazard, and is well justified regardless of any real or imagined economic impact. Finally, this smoke-free indoor air law in Delaware's hospitality industry appears to have resulted in an unintended but welcome 11% decline in statewide smoking prevalence after only one year, with a much greater 25% decline among 18 to 24 year olds.

Conclusions

This study assessed air quality in eight hospitality industry venues in the Wilmington, Delaware, metropolitan area before a smoking ban, using state-of-the-art real-time respirable particulate air pollution and respirable particulate carcinogen monitors calibrated against SHS. It was discovered that despite the low smoking prevalence observed, averaging approximately two thirds of the statewide smoking prevalence of 23%, all venues were heavily polluted with fine RSP, violating the US annual NAAQS for respirable particulate air pollution for hospitality workers by an average of 4.6 to 1, raising occupants' risk of cardiopulmonary disease. The 24-h average levels of PPAH were increased over background levels in the eight venues by an average of nearly 3:1, and the short-term work shift exposures by 5:1 relative to postban levels, raising occupants' risk of cancer, heart disease, and stroke. Presmoking ban indoor carcinogenic PPAH and RSP levels for the eight venues exceeded those measured on I-95, a heavy truck route, during rush hour on one of the major East-Coast US interstate highways. During smoking, for the eight hospitality venues overall, an estimated average of 96% of the indoor RSP pollution and 84% of the indoor PPAH carcinogens were caused by SHS, using measured outdoor levels as the reference level. Using postban indoor air concentrations as the referent, 90% of the RSP and 95% of the PPAH carcinogens can be attributed to tobacco smoke. Delaware's comprehensive smoking ban has significantly reduced the risk of cancer, heart disease, stroke, and respiratory disease among workers and patrons in its hospitality industry.

Acknowledgments

This work is supported by the Robert Wood Johnson Foundation Innovator Award. The author is grateful to Ms. D. Brown of the American Lung Association of Delaware for financial and logistical support, and to J.W. Repaci for outstanding computer support.

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