Controlling Tobacco Smoke Pollution

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Secondhand smoke (SHS) is a dangerous, often unregulated, environmental pollutant that causes cancer and heart disease in adults and respiratory disease in children. Smoking bans eliminate these risks. However, some groups insist that ventilation, which inevitably leaves residual smoke in the air, can provide acceptable indoor air quality.

How does ventilation compare to smoking bans in controlling SHS in hospitality venues? On Nov. 27, 2002, Delaware banned smoking in all restaurants, bars and casinos, with the intent of giving hospitality workers the same occupational health protection that other workers had enjoyed since 1994.

This afforded an opportunity to investigate contemporary levels of SHS in the hospitality industry. I conducted an indoor/outdoor air quality study in the Wilmington, Del., metropolitan area before and after the enactment of Delaware's clean indoor air law.[1] *Table 1* describes the venues investigated, including a casino, six bars, and a pool hall.

The pollutants measured were respirable particulate matter (RSP) and particulate polycyclic aromatic hydrocarbons (PPAH), which are emitted by cigarettes, pipes, and cigars. These pollutants are also known to be involved in the induction of cancer, respiratory disease, heart disease, and stroke. RSP is also a regulated outdoor air pollutant, while PPAH contains 10 known carcinogens, and causes arterial wall damage.[1,13,14]

Equipment & Methods

I deployed concealed continuous real-time monitors for RSP, i.e., airborne particulate matter in the combustion range below 3.5 microns in diameter ($PM_{3.5}$), and PPAH, as well as carbon dioxide, carbon monoxide, temperature, and relative humidity. All indoor venues visited were selected by personnel of the American Lung Association of Delaware to represent a cross-section of the spectrum of area hospitality venues.

Visits averaged ~30 minutes. For comparison, I sampled outdoor pollutants on city streets, on Interstate 95 in heavy traffic during rush hour, and in a nonsmoking hotel room.

Monitoring was conducted on Nov. 15, 2002, prior to the smoking ban, and again on Jan. 24, 2003, two months after the ban. All monitoring equipment was synchronized to an atomic clock signal via computer; venue visiting times were recorded in a diary. The area, volume, number of persons, and average number of active smokers were recorded for each venue to generalize the results.

Predicting SHS Concentrations

Respirable particulate air pollution concentrations from SHS (SHS-RSP) are directly proportional to the smoker density and inversely proportional to the air-exchange rate, and can be quantified using the time-averaged mass-balance model, or Habitual Smoker Model (HSM).[2–5] A habitual smoker is defined as smoking two cigarettes per hour at 10 minutes per cigarette.[3,4] Thus, for every three habitual smokers, one cigarette burns constantly on average.

Equation 1 gives SHS-RSP in units of micrograms of RSP per cubic meter of air (μg/m^3), from the ratio of the active smoker density D_s, in units of average number of burning cigarettes per hundred cubic meters (BC/100 m^3) in the space, to the air exchange rate Q_v, in air changes per hour (h^{-1}), where the constant 650 incorporates a 30% default RSP surface deposition term, and assumes 14 mg SHS-RSP per cigarette.[2,12]

$$SHSRSP = 650\ \frac{D_s}{Q_v}\quad (\mu g/m^3) \tag{1}$$

Since Equation 1 predicts the time-averaged value of the SHS concentration, it does not require that the concentration be constant during the observation period for accurate predictions but assumes that the initial and final conditions are the same.

When used to analyze actual measured data, a "trend correction term" $\Delta X/Q_vT$ may be required if this quantity is significant compared to the time-averaged value of SHS-RSP, where ΔX is the difference between the initial and final SHS concentrations, and T is the observation time.[5] However, the trend correction term disappears when ΔX is zero, or can be

Venue	Description
A. Casino	Large volume slot machine-only casino with restaurant/bar areas, all smoking; one relatively small nonsmoking 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	Stand-up/sit-down smoking bar area with adjacent dining table area; located in a midsize 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 bar stools 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	Stand-up/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.

Table 1: Eight Wilmington, Del., hospitality venues in which air quality measurements were made; areas described as "smoking" were smoking on Nov. 15, 2002, and nonsmoking on Jan. 24, 2003, after the ban. These venues were chosen from across the spectrum of available hospitality types.

neglected when T is very large compared to $\tau = 1/Q_v$, where τ is the residence time for smoke in the air.[5]

In many practical cases, SHS-RSP over the observation time is approximately constant in a space with many smokers, and the trend correction term can be neglected.

The HSM is used to predict SHS-RSP for a bar as follows: the Delaware smoking prevalence is 23%. For a bar with a default occupancy of 100 persons per 1,000 ft^2* and a 10 ft* ceiling, the metric volume is 283 m^3, and the habitual smoker density D_{hs} = (0.23 smokers/person)(100 persons)/283 m^3 = 8 habitual smokers per 100 m^3,* of whom an average of one-third are assumed to be actively smoking during any 10 minute period. Thus, the density of active smokers expected to be observed in a Delaware field survey is given by $D_s = D_{hs}/3$ = 2.7 burning cigarettes per 100 m^3.

The default air-exchange rate is estimated from ANSI/ASHRAE Standard 62-1989, *Ventilation for Acceptable Indoor Air Quality*, which prescribed 30 ft^3 of outdoor air per minute per occupant (ft^3/min-occ) for smoking bars. Thus Q_v = (30 ft^3/min-occ)(100 occ/10,000 ft^3)(60 min/hr) = 18 air changes per hour.

Using Equation 1, the estimated respirable smoke particulate (RSP) concentration ($PM_{3.5}$) for a Delaware bar under the ASHRAE default assumptions for smoking occupancy and ventilation, is: $\text{SHS-RSP}_{pub} = 650\, D_s/Q_v = 650(2.7)/(18)$ = 98 µg/m^3.

If we add the expected outdoor background RSP level of 16.6 µg/m^3 to this value (the 2003 annual average from the New Castle County, Del., outdoor air quality monitoring network), since outdoor RSP easily penetrates indoors, we would expect to find a typical total RSP level of (98 µg/m^3 + 17 µg/m^3) = 115 µg/m^3 in a Delaware bar ventilated according to Standard 62-1989.

Applied to the analysis of a specific bar whose indoor/outdoor RSP concentrations and smoker density have been measured, the HSM can be used to estimate the air-exchange rate.

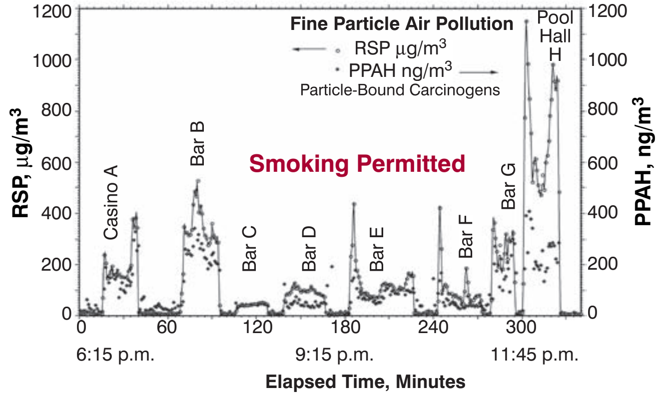
Field Measurements and Results

Figure 1 shows the real-time measurements performed on Nov. 15, 2002, before the smoking ban. The large peaks from the indoor smoke-filled venues loom far above the much cleaner outdoor air. Measurements of total RSP, averaged over the six bars in *Figure 1*, yield a mean of 160 µg/m^3 (standard deviation [SD] = 111 µg/m^3), with a median value of 115 µg/m^3. Thus, the median default prediction (above) and the global median value are in good agreement because both the measured six-bar median smoker density and estimated air exchange rate were 10% of expected: The expected D_s was 2.7, the actual values ranged from 0.02 to 1.4, and averaged 0.47 (SD = 0.56), and the median was 0.24. The expected Q_v was 18 h^{-1}, the estimated values for the six bars using the HSM ranged from 0.3 to 3 h^{-1}, with a mean of 1.5 h^{-1} (SD = 1), and a median of 1.5 h^{-1}.

Figure 2 shows the corresponding measurements in the same venues performed on Jan. 24, 2003, after the smoking ban, with dramatically lower pollution levels. Post-ban, it is nearly impossible to distinguish between indoors and outdoors except for the pool hall, which has another indoor source, possibly chalk dust from the pool cues.

Figure 3 shows that both RSP and PPAH increase markedly with smoker density, as the model predicts. PPAH does not show as strong a variation with air exchange rates as RSP, because controlled experiments show that due to enhanced

* 100 persons/100 m^2; 10 ft = 3.05 m; 30 cfm/occ = 15 L/s.



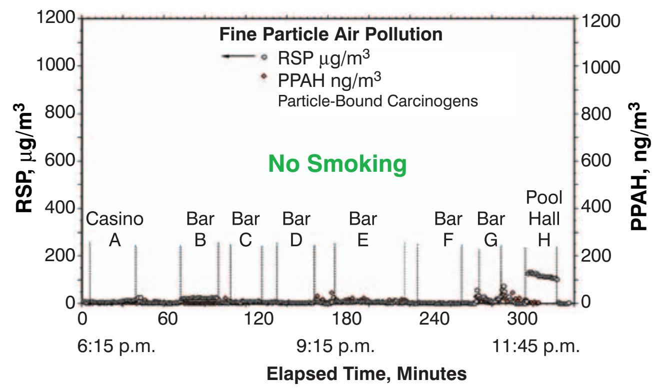


Figure 1 (left): Real-time RSP air pollution and PPAH outdoors and in a casino, six bars and a pool hall before a smoking ban.[1] For comparison, the NAAQS for fine-particle air pollution ($PM_{2.5}$) is 15 $\mu g/m^3$, the annual average level defining clean air. Figure 2 (right): RSP air pollution and PPAH in the same venues after the smoking ban.[1]

surface deposition, SHS-PPAH decays twice as fast as SHS-RSP.[1] The ratio of RSP/PPAH was found in controlled experiments to be 2,000:1.

Prior to the smoking ban, all venues were heavily polluted, with indoor RSP levels averaging 20 times outdoor background. For workers, these levels violated the annual National Ambient Air Quality Standard (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 pre-ban indoor carcinogenic PPAH averaged five times higher than outdoor background levels, tripling workers' daily exposure, and exceeding PPAH measured at an I-95 tollbooth at the Baltimore Harbor Tunnel.

Comparing the indoor and outdoor data in *Figure 1*, and the data in *Figure 1* to *Figure 2*, 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 35% lower than the statewide average.

This air quality survey has demonstrated conclusively that the health of hospitality workers and patrons was endangered by SHS pollution. The Delaware Clean Indoor Air Act's ban on smoking in hospitality workplaces eliminated that hazard. As *Figure 3* shows, and CO_2 measurements support, there is substantial under-ventilation of all venues. For the four bar venues (B–E) for which reliable pre- and post-ban air exchange rate comparisons could be made (pre-ban calculated from the data by the model and post-ban from CO_2), the median pre-ban rate was 1.85 ACH vs. a post-ban median of 1.34 ACH, which was far below the 18 ACH expected. While the smoker densities are lower than expected, so are the air-exchange rates, and the model applied to the data allows us to understand why the concentrations are what they are, and, therefore, generalizes the results.

This raises two important questions: if these venues had actually been ventilated according to Standard 62-1989, would it have been enough to provide acceptable indoor air quality? And since no cognizant authority has actually defined an acceptable level for SHS, can we estimate what level of SHS might be acceptable?

Guidance on these questions can be derived from American and Australian ventilation standards, and from the air quality standards, practices, and proposed rules of U.S. regulatory agencies.

Minimum Ventilation Rates for SHS Control

After 30 years of recommending ventilation rates for the control of tobacco smoke odor, Standard 62.1-2004 revised the Minimum Ventilation Rate Table to apply only to no-smoking spaces, recognizing the mortal hazard of SHS as defined by cognizant authorities.[16] However, Standard 62.1-2004 requires additional (but unspecified) ventilation in excess of the table rates for engineers designing for smoking venues.

For a given level of smoking, is it possible to estimate how much additional dilution ventilation might be required to attain acceptable indoor air quality? This can be approached in two ways, both of which use the indoor air quality procedure of Standard 62.

Particulate Phase Control

First, consider SHS as just simple particulate pollution. One guideline recommended by Standard 62.1-2004[16] for assessing indoor air quality is the U.S. NAAQS. The NAAQS for $PM_{2.5}$ is designed to protect against respirable particle health effects such as premature death, increased hospital admissions, and emergency room visits, primarily among the elderly and individuals with cardiopulmonary disease; increased respiratory symptoms and disease in 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.

How much ventilation would it take to satisfy NAAQS? To satisfy NAAQS *de facto*, a worker's weighted annual average exposure needs to be $\leq 15\ \mu g/m^3$. Suppose the outdoor annual average RSP level were 10 $\mu g/m^3$, at the low end for all U.S. counties. The modeled SHS-RSP concentration for a bar is 98 $\mu g/m^3$. Then, a calculation of the time-weighted annual average exposure for bar staff, assuming an eight-hour workday and a 250 day work-year, yields a maximum permissible indoor SHS-RSP concentration of 22 $\mu g/m^3$.

Using the HSM, it is easily calculated[1] that the minimum necessary air exchange rate would have to be ≥ 80 air changes per hour (ACH), equivalent to 133 cfm/occ (a ~15-fold increase over the 9 cfm/occ recommendation for bars from Standard 62-2004).

Suppose the outdoor air level were to average 14 $\mu g/m^3$. In that case, the required bar air-exchange rate Q_v increases to 400 ACH or 665 cfm per occupant (occ). At the actual 16.6 $\mu g/m^3$ outdoor air average, NAAQS can never be attained unless the outdoor air supply is cleaned with a fine particle filter.

However, even if NAAQS could be met, how could the practitioner be assured that the residual SHS concentration was safe for occupants to breathe from a carcinogenic and toxic standpoint? This leads us to the Australian approach.

SHS Carcinogen and Toxin Control

Australian ventilation engineers developed informative guidance called the Environmental Tobacco Smoke Harm Index (ETSHI) (AS 1668.2 Supplement 1—2002),[6] based on a scientific report of the Australian National Health and Medical Research Council.[7] The Australian methodology is equivalent to applying the Indoor Air Quality Procedure of Standard 62-2004.

The ETSHI is used to estimate the mortality risk associated with a specified exposure to SHS in an environment that is ventilated and that may be fitted with an air cleaner. Appendix A of the ETSHI guidance estimates the combined lung cancer and heart disease mortality risk for office workers in a typical smoking-permitted office as: ETSHI = 225 deaths per million exposed Australian office workers per year. This is similar to an estimate for U.S. office workers of 244 deaths per million per year, made using the defaults of the old Standard 62-1989, which recommended ventilation rates for smoking venues.[8] The default assumptions for both Australian and U.S. office workers are the same: 10 persons per 100 m^2 of occupiable space and a ventilation rate of 10 L/s-occ. The smoking prevalence for the Australian case was 33%, and in the U.S. case was 29%. Normalized for smoking prevalence, these risk estimates[6,8] differ by less than 15%, and are likely due to the use of particulate air filtration in the ETSHI calculation.

The ETSHI for office workers is readily scaled to bar workers. As the calculation under Equation 1 showed for the default bar, a concentration of 98 $\mu g/m^3$ resulted for a smoking prevalence of 23%. Scaling that to the 33% of the Australian office assumption, that increases to $(0.33/0.23)(98) = 141\ \mu g/m^3$. For the default Australian office, the smoker density is $D_s = D_{hs}/3 = 0.39$. The default air exchange rate is 1.2 ACH, neglecting any additional air cleaning as the tobacco aerosol is submicron in size.

Using Equation 1, the predicted respirable smoke particulate (RSP) concentration ($PM_{3.5}$) for an Australian office is calculated as: $\text{SHS}-\text{RSP} = 650(0.39)/(1.2) = 211\ \mu g/m^3$.

Thus, assuming a 33% smoking prevalence, the ETSHI for the default U.S. bar is scaled as $(141/211)(225) = 150$ deaths per million per year, or in a 45-year working lifetime, an estimated 6,750 deaths per million persons at risk, or a working lifetime mortality rate of 7 per 1,000.

By comparison, U.S. Occupational Safety and Health Administration (OSHA) estimated in 1994 a working lifetime risk to U.S. workers from SHS ranging from 7.4 per 1,000 to 17 per 1,000.[8,10]

How big are these risks? OSHA defines a risk of 1 per 1,000 as a "significant risk of material impairment of health." OSHA, a cognizant authority,[15] stated that, for mortality rates of this magnitude, "the significance of risk is very great."[10] Risks in excess of 3 per 10,000 are invariably regulated.[9]

Although no cognizant authority has set an acceptable level for SHS *per se*, we can ask if there is some level of mortality *risk* that federal regulatory agencies have viewed as acceptable? For guidance on this issue,[8] we turn to a Harvard University review of 133 U.S. regulatory decisions. The risk management decision rule employed by federal regulatory agencies such as OSHA, Environmental Protection Agency (EPA), and Food and Drug Administration for carcinogens and toxins in air, water, or food is called *de minimis risk*, i.e., a lifetime risk "beneath regulatory concern."[9] This level is typically one death per million persons per lifetime.[8,9]

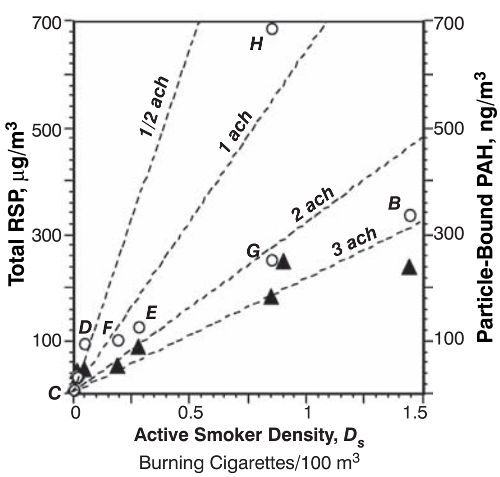


Figure 3: Air pollution in seven of eight hospitality venues where smoking occurred (smoker density not recorded for Casino A), and a Delaware nonsmoking hotel room on Nov. 15, 2002.[1] Both RSP and PPAH increase with increasing D_s. Data points B-G are the six bar venues. Circles represent RSP. Triangles represent PPAH.

OSHA failed to promulgate a rule governing the private sector, eventually withdrawing its proposed rule in 2001 (66 FR 64946) due to heavy Congressional pressure to leave SHS regulation up to the states.[1] Nevertheless, all federal workplaces have become smoke-free, and Congress itself legislated smoking out of airlines, which were not under OSHA's jurisdiction.[17]

However, states have been slow to act. To date, only nine—California, Connecticut, Delaware, Maine, Massachusetts, Montana (delayed until 2009) New York, Rhode Island, and Vermont (effective in Fall 2005)—have adopted smoke-free workplace laws that protect all workers. In 1997, the California EPA estimated total U.S. mortality from SHS at 38,000 to 65,000 per year.[11] By comparison, drunk driving-related deaths in 1997 totaled 16,000.

How much additional ventilation would be required to attain *de minimis risk* from SHS in the default U.S. bar described previously? If this risk reduction is to be achieved by ventilation alone, since risk is inversely proportional to ventilation rate, to reduce the risk to acceptable levels for bar workers, the ventilation rate would have to be increased by the ratio of the number of estimated deaths to the *de minimis risk*: a factor of 6,750:1, or to 6,750 × 30 cfm/occ = 202,500 cfm/occ, based on Standard 62-1989.[15] However, the default ventilation rate for a smoke-free bar under Standard 62.1-2004 is 9 cfm/occ (equivalent to 5.4 ACH). Thus, the amount that the ventilation rate would have to be increased over the smoke-free case is (202,500/9) = 22,500 times, and the corresponding estimated air-change rate required for acceptable indoor air quality would be 22,500 × 5.4 = 121,500 ACH, which would require a veritable indoor tornado. Even greater airflow rates would apply for air cleaning, which inefficiently removes SHS gases.

The conclusion is that ventilation technology cannot possibly achieve acceptable indoor air quality in the presence of smoking, leaving smoking bans as the only alternative.

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