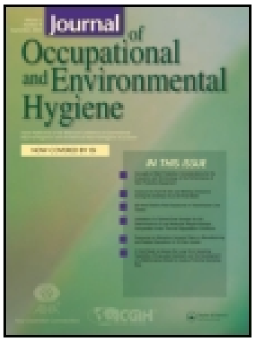

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Estimating Personal Exposures Based on Mass Balance Material Usage Rates: Validation of a Ventilation Model in a Spray Paint Booth

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The goal of this research was to evaluate an estimating model (box model) with direct measurements of contaminants in an industrial spray painting operation. The research involved a dilution ventilation efficiency experiment that was devised to estimate the effective ventilation rate, sampling for organic compounds (xylene, ethyl benzene, methyl ethyl ketone, and methyl isobutyl ketone) in a paint booth, and simultaneously measuring the mass usage of these compounds during painting operations in order to compare measured with predicted concentrations. The results of the dilution ventilation experiment indicated that channeling of air was occurring due to a high ventilation rate in the painting area. The results of the mass balance usage and air sampling comparisons indicated that predicted concentrations were within the 95% upper/lower confidence interval about the geometric mean in 14 out of 16 area samples taken within the paint booth (87.5%). Correlation analysis between predicted concentrations and area, personal, and exhaust stack concentrations were strongest with exhaust ($r = 0.923$). Correlations with personal concentrations were not as strong ($r = 0.828$), and the area concentrations were even less strong (0.757). In conclusion, the box model does appear to be a useful additional tool for estimating worker exposures. However, the characteristics of any particular ventilation system must be understood before modeling is conducted.

Keywords box model, dilution ventilation, mass balance, personal exposures, paint-booth exposure estimates, risk assessment

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INTRODUCTION

Workplace hazard evaluation is one of the most important duties required of an industrial hygienist. With regard to airborne hazards, the evaluation process often involves the application of a time-consuming sampling process that may require costly lab-based methods as well as direct-reading instruments. Results from this process, however, are only applicable to the process conditions occurring during sampling. If operations change and/or new materials are introduced, as is frequently the case in the modern business climate, new sampling episodes must be initiated. To avoid unnecessary sampling, contaminant estimation models may be used to limit the uncertainty and range of possible exposures, allow for proper sample loading on the sampling media, and prioritize sampling strategies. Furthermore, given a valid relationship between an exposure model and direct measurement, the impact of future operational usages can be accurately predicted.

Contaminant estimation models for indoor air pollutants can be developed over a wide range of complexity. Simple "saturation" or "zero ventilation" models predict worst-case scenarios by assuming no dilution within a space via general ventilation.(1,2) The complicated computational fluid dynamic models incorporate detailed physical aspects of a ventilated area to model contaminant concentrations in multiple areas within a ventilated space.(3–5) Nicas(6) simplified that approach by focusing on a typical industrial situation where a room can be considered to contain just two zones defined by a well-mixed upper zone near the inlet and exhaust locations, and an imperfectly mixed lower zone. Modeling that simply considers a room as a single zone, or "box," has also been developed under the assumption that the entire room is well-mixed by ventilated air.(1,2,7–12) Modeling has also been applied to ventilated areas such as spray booths where large airflows are forced longitudinally through the room volume creating high turbulence.(4,13–15)

The development of a box model to estimate airborne contaminant concentrations is based on the mass rate of change of compounds used during the industrial process. In the case where the generation rate is not constant and/or the contaminant is removed by factors other than dilution, a non-steady-state differential equation can be constructed to determine the contaminant concentration over time:(1)

$$V\frac{dC_{room}}{dt} = QC_{in} - QC_{out} + G - RC_{room} \qquad \textbf{(1)}$$

where V is the room volume (m^3); t is time (hr); Q is the measured ventilation rate of air through the room (m^3/hr); C_{in}, C_{out}, and C_{room} are the concentrations (mg/m^3) entering, exiting, and existing in the room at any given time; G is the mass generation rate going into, or generated within, the room (mg/hr); and R is a factor (m^3/hr) to account for the removal rate by mechanisms other than ventilation and filtration such as compound reactions over time. Under the simplest conditions where $R = 0$, $C_{in} = 0$, and, at steady-state, $dC/dt = 0$, Equation 1 results in a simple equation that directly relates the steady-state concentration, C_{eq}, to G and Q in a completely-mixed room:

$$C_{eq} = G/Q \qquad \textbf{(2)}$$

Use of Equation 2 to model exposures may not be accurate because a room is rarely ventilated to achieve complete mixing. A correction factor, k, based on ventilation configuration, can be applied to Equation 2.(12) This correction factor may be used to designate an "effective" ventilation rate, $Q_{eff} = Q/k$, resulting in the more accurate box model:

$$C_{eq} = Gk/Q \qquad \textbf{(3)}$$

However, tracer gas analysis techniques can be used to empirically determine k.(10) When using this method, a tracer gas is generated in a room and allowed to build up to a steady concentration, the gas source is then turned off ($G = 0$), and the concentration is allowed to decay while being measured with a direct-reading instrument. The solution of Equation 1 by integration when $G = 0$, $C_{in} = 0$, and $R = 0$, and including k, results in an expression that best models the resulting decay curve:

$$C = C_o \exp\left(-\frac{Q}{kV}t\right) \qquad \textbf{(4)}$$

where C_o is the concentration reached prior to turning off the gas generation. The linear form of Equation 4 is:

$$\ln C = \ln C_o - \frac{Q}{kV}t \qquad \textbf{(5)}$$

and, therefore, the slope, s, of this linear relationship is equivalent to $-Q/kV$. A least-squares regression analysis of the decaying gas concentrations can be used to determine this slope and thus solve for k.

Specific objectives of this study were (1) determination of ventilation characteristics (k) needed in the estimating box model by direct measurements of a tracer gas, and (2) validation of the model by comparing the calculated estimates with direct measurements of several compounds used in an industrial spray painting operation. The goal of this research was to evaluate the effectiveness of using the box model for predicting the contaminant concentration in an industrial setting. As part of this research, model-based estimates of concentration were compared to personal measurements, area measurements, and measurements taken within the room exhaust vent.

We expected that exhaust measurements would be best correlated with model estimates because these concentrations (C_{out}) are directly linked to the model derivation. However, the ultimate utility of such a model is to estimate potential personal exposures. Therefore, we also compared personal measurements to model estimates knowing that personal concentrations result from conditions that may violate model assumptions, such as variations in area concentrations.

METHODS AND MATERIALS

Facility Description

A facility with a paint booth that resembled a well-mixed box (Figure 1) was selected to validate the steady-state model (Equation 5) in an industrial setting. The booth measured 5.7 m wide × 9.1 m long × 3 m high. The study facility manufactures mining, agricultural, and marine equipment. A batch process is used to paint the parts. First, a group of parts is brought into the paint booth after being cleaned in a vapor degreaser. The parts are placed on steel mesh tables. Most of these tables are located on the left side of the paint booth. After the parts are arranged on the tables, the parts are spray painted on one side with a primer, left to dry, then turned over and spray painted on the reverse side. The parts are then spray painted with an adhesive coating, left to dry, then turned over and spray painted on the reverse side. One batch typically takes 1 hour.

Model Use

Because the paint booth described above was operated in batches, the process did not result in maintaining an ideal, steady-state concentration within the paint booth. However, the steady-state box model defined by Equation 3 was utilized for comparison with actual contaminant measurements. To apply Equation 3 to this process rather than the time-varying equation described by Equation 1, several simplifying assumptions were made: removal mechanisms other than by ventilation were negligible ($R = 0$), and there was no change in concentration over time ($dC/dt = 0$). Furthermore, the lack of contaminant in incoming makeup air was confirmed by sampling ($C_{in} = 0$). In order to directly compare C_{eq} with G in Equation 3, a time-weighted average concentration was computed for a sampling period corresponding to the time during which all contaminant mass was generated.

Mixing Factor Determination

A determination of the value of the mixing factor, k, with the use of Equation 5 required knowledge of the flow rate through the room, Q, the room volume, V, and readings of the tracer concentration, C, over time. An analysis of the air velocity through the room was also conducted to determine whether turbulent mixing conditions existed in the room.

The airflow rate through the room was determined by measuring the flow rate of air through the roof exhaust duct according to U.S. Environmental Protection Agency (EPA) Methods

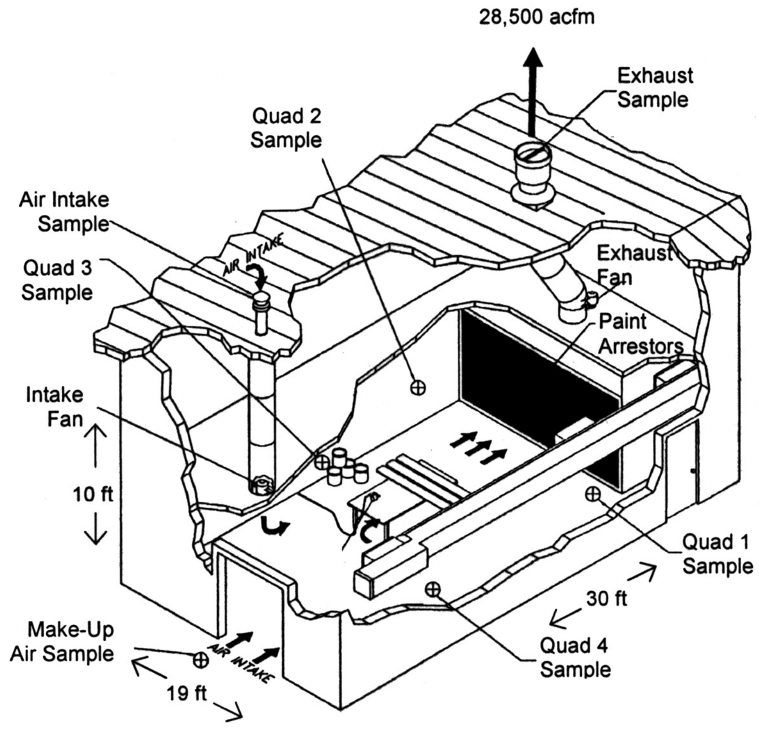

FIGURE 1. Paint booth layout and sample locations

1 through 4.(16) This was done by first taking into account flow disturbances upstream and downstream of the roof exhaust sampling ports. An S-type pitot tube connected to an inclined manometer was used to measure exhaust gas velocity. Temperature was measured with a type K thermocouple attached to a calibrated digital temperature indicator. The molecular weight of the exhaust gas was determined by an Orsat analyzer (Burrell Corp., Pittsburgh, Pa.) and the moisture content by weighing the impingers before and after the tests.

Schematic diagrams of the paint booth were used to determine the room volume, V. The average air velocity within the paint booth was measured with a velometer (Velocicalc, TSI, St. Paul, Minn.) placed in a grid pattern at various distances from the exhaust outlet throughout the paint booth. An average velocity through the room was determined from these measurements and the Reynolds number, R, was calculated to indicate the amount of turbulence, and therefore mixing, in the room:

$$R = (UD\rho)/\mu \qquad \textbf{(6)}$$

where U is the air velocity (m/s), D is the hydraulic diameter of the room (m), ρ is the density of air (kg/m^3), and μ is the viscosity of air (kg/m × s). Reynolds numbers above 2000 are considered turbulent.

A compressed cylinder of carbon dioxide (CO_2) was used as the generation source of a tracer gas through the paint booth. Although CO_2 is somewhat reactive, this gas was chosen because a portable direct-reading and recording device (Q-Trak, TSI) for measuring CO_2 was small enough to be placed in the booth without interfering with work practices. After measuring ambient levels, a gas monitor was placed in the middle of the paint booth to indicate the influence of the ventilation system on concentrations in the work area of the booth. Next, CO_2 was introduced into the paint booth from the gas cylinder and raised to several thousand ppm before the gas cylinder was shut off. The decay of the CO_2 gas from its steady-state level to ambient levels was recorded by the gas monitor during four experiments. After subtracting the minimum ambient level from all recorded values, the decay curves were then graphed on semi-log paper and regression analysis was performed on the now-linear decay curves to determine the value of k from the slope of the linear equation described by Equation 5. An overall k value used to produce model estimates was determined from the average of the four k values obtained during these trials.

Chemical Compounds

After determining k from the studies described above, the accuracy of the box model described by Equation 3 was evaluated by measuring the concentrations of various gases emitted by compounds used in the paint booth and comparing these results to the predicted values. The paint used at the test facility contained xylene (XYL), ethyl benzene (ETB), methyl ethyl ketone (MEK), and methyl isobutyl ketone (MIK). Both MEK (with the primer) and XYL (with the adhesive) were used as thinners. The paint and thinner mixture was applied with a handheld air-atomized spray gun from a 5-gal mixture. All paint materials were kept within the paint booth during mixing and application. Cleaning of paint application tools was also performed within the paint booth. These target volatile organic compounds (VOCs) were selected based on their high concentration within the paints and thinners used in this process and because they could be sampled simultaneously on the same charcoal tube (National Institute for Occupational Safety and Health [NIOSH] Method 1501).

To use the box model, the generation rate, G, of each compound had to be computed. To determine G for each compound, the amount of paint and thinner used during a sampling episode was weighed before and after the sampling period. For example, if a gallon of paint with a density of 10 lbs/gal was used, and the material safety data sheets indicated that the paint was 40% by weight XYL, an estimation of 4 lbs of XYL was ascertained. The rate at which the XYL was emitted was then assumed to be constant over the sampling time and equal to the amount used divided by the sampling time. Given the determined values of k and G, and the known value of Q, the box model was used to estimate concentrations for comparison with the measured values.

Sampling Locations and Analysis

The sampling locations within and without the paint booth are identified in Figure 1. Seven sample locations were established for each sampling episode. Four area samples were located inside the paint booth and spaced in such a way as to obtain samples representative of the four quadrants (Quad) of the room defined by position relative to the entry door as follows: Quad 1-far right, Quad 2-far left, Quad 3-near left, and Quad 4-near right. These multiple locations were sampled within the room to determine a spatial average concentration within the room and to determine whether there were large differences between locations.

A sample was also taken at the fresh air intake (to assure that air contaminants were not being short circuited into the paint booth), inside the plant (but outside the paint booth near the entrance door), and within the exhaust stack on the roof. The sample that was located outside the paint booth entrance door was used to verify that contaminants from inside the plant were not entering the paint booth ($C_{in} = 0$).

A personal sample was also collected from the spray painter during each sampling episode. The spray painter was not inside the paint booth during the entire sampling episode, but came in and out of the paint booth performing other work while waiting for the parts to dry. During each hour the sprayer spent approximately 15 min within the booth and parts were left to dry during the remaining time. The spray painter, however, was in close proximity to the volatile organic spray mixture during the highest potential exposures, that is, paint/solvent preparation, actual painting, and cleanup while in the paint booth.

Direct sampling with pumps and charcoal tubes was conducted simultaneously at the locations identified in Figure 1. Four sampling episodes were planned on consecutive weeks with four samples taken for each analyte per sampling episode. NIOSH Method 1501 was used to conduct the sampling and analysis. NIOSH Method 1501 was developed and evaluated for use in analysis of benzene, cumene, a-methylstyrene, styrene, vinyl toluene, p-tert-butyl toluene, ETB, naphthalene, toluene, and XYL. The inclusion of MEK and MIK in the analysis is considered a modification of this method.

The required sampling times were calculated based on work schedules and VOC measurements (2000 ppm) taken with a photoionization detector (Microtip, Photovac Incorporated, Deer Park, N.Y.) during previous painting episodes. Sampling episodes of approximately 2 hours were estimated. Low flow rates of 50 mL/min were used in areas where VOC concentrations were expected to be high. Higher flow rates of 200 mL/min were used for areas that were considered relatively free from contaminants (e.g., outdoor air, recycled air). The samples were collected on charcoal tubes with volumetric pumps that do not decrease in flow rate when loaded (Escort, MSA Corporation, Pittsburgh, Pa., and Airchek 224-52, SKC Inc., Eighty Four, Pa.). The pumps were pre- and postcalibrated with a primary airflow meter (DryCal® DC-1, Bios International Corporation, Pompton Plains, N.J.).

Sampling was performed during the entire timeframe that any particular batch of parts was painted, including drying time. Samples were then collected, capped, and stored in a cooled container during transportation to the laboratory. Field blanks were used for each set of samples. The University of Iowa Hygienic Laboratory, Iowa City, Iowa, which performed the analysis, is accredited by the American Industrial Hygiene Association (AIHA) for organic solvents (laboratory #102530).

Statistical Analysis

Excel 2000 was used for data management and statistical analysis. Data were log-transformed and geometric mean concentrations with 95% confidence levels were calculated for each analyte measured. In the few cases with data below detection limits, half the LOD was used to allow statistical calculations. Pooled coefficients of variation were also calculated to evaluate variability by location in the paint booth. Pearson correlation coefficients (r) were also used to evaluate relationships between predicted airborne concentrations and measured concentrations in area, personal, and exhaust samples.

RESULTS

Air velocities (ft/min) measured within the paint booth are given in Figure 2. Velocities were generally uniform in the 400 ft/min (2.0 m/sec) range as the air passed through the entry door. A tunneling effect apparently occurred as the air moved through the paint booth, as velocities were greatest in the right-center of the paint booth. However, velocities at the filters were more evenly distributed. The airflow rate through the room was 13.4 m^3/sec (28,500 acfm) and the room volume was 161 m^3. Given an average velocity, $U = 0.775$ m/sec, and

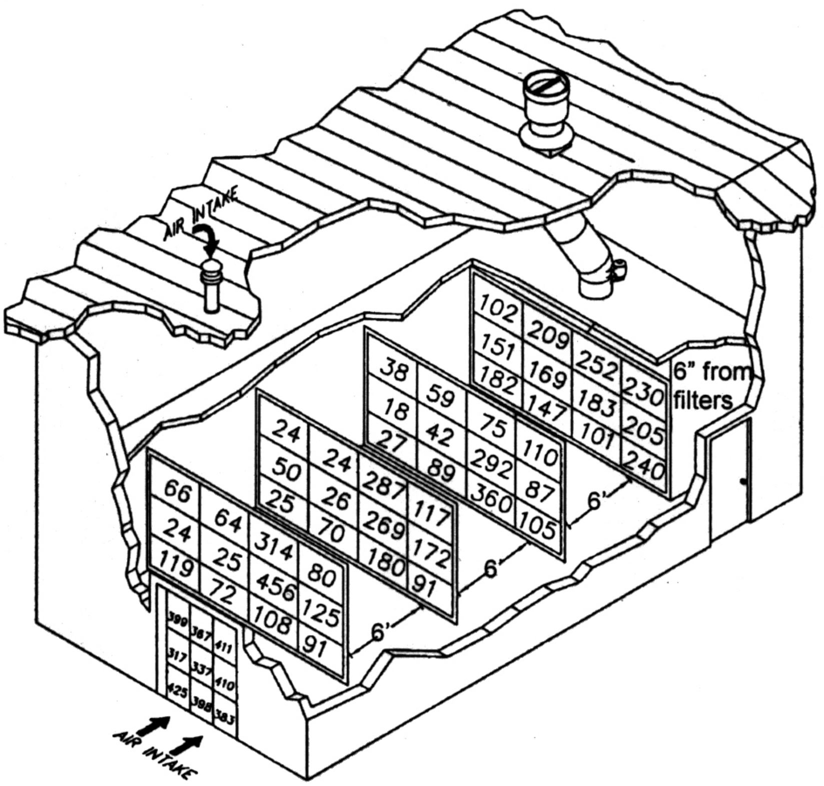

FIGURE 2. Measured airflow rates (ft/min) at various locations within the paint booth

$D = 4.7$ m, $\rho = 1.2$ kg/m^3, and $\mu = 1.8 \times 10^{-5}$ kg/m × s, the paint booth Reynolds number was 242,800. This high value indicated a very turbulent airflow and the potential for good mixing.

A typical CO_2 decay curve, after subtracting background concentrations, is given in Figure 3. Figure 4 reveals the same curve on semi-log graph paper. From the slope shown in Figure 4, and given the reported values of Q and V, a k value of 0.80 was determined with the use of Equation 5. The average of the k values obtained during these four experiments was 0.87. This value for k was applied to Equation 3 to predict concentrations such as the estimated amount of each analyte generated within the paint booth during the sampling period (G) and the flow rate (Q).

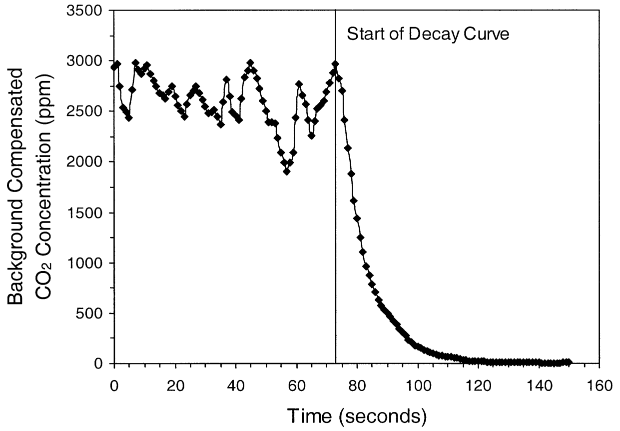

FIGURE 3. Carbon dioxide decay curve measured in center of booth

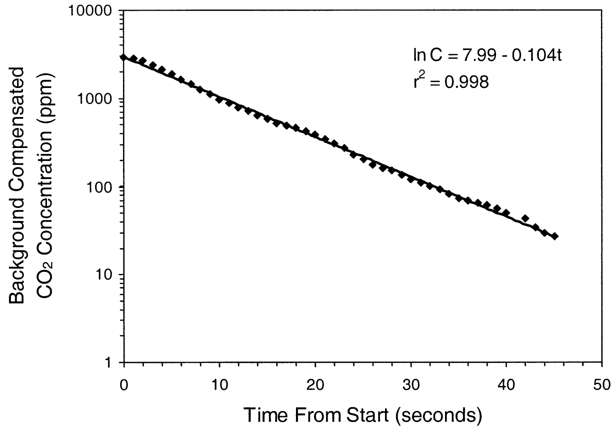

FIGURE 4. Linear transformation and regression of carbon dioxide decay curve

TABLE I. Predicted Concentration Compared to Geometric Mean of Room Area Concentrations with 95% Confidence Intervals (CI) for Each Sample Day

Sample Day	Analyte[A]	Room (mg/m^3)	CI (mg/m^3) Lower	CI (mg/m^3) Upper	Predicted[B] (mg/m^3)
Day 1 AM	ETB	1.7[C]	0.3	8.6	2.9 X
Day 1 PM	ETB	1.2[C]	0.6	2.4	2.0 X
Day 2 AM	ETB	3.5	0.9	13.0	7.4 X
Day 2 PM	ETB	2.9	1.1	7.3	1.3 X
Day 1 AM	MEK	1.4[C]	0.3	6.4	3.1 X
Day 1 PM	MEK	1.3[C]	0.6	3.2	1.7 X
Day 2 AM	MEK	7.6	3.7	15.7	5.9 X
Day 2 PM	MEK	3.0	1.8	5.1	1.0
Day 1 AM	MIK	3.2[C]	0.6	17.4	6.9 X
Day 1 PM	MIK	2.2[C]	0.6	8.4	3.7 X
Day 2 AM	MIK	7.9	3.0	21.3	13.2 X
Day 2 PM	MIK	5.3	2.4	11.5	2.1
Day 1 AM	XYL	9.1	2.1	39.8	17.2 X
Day 1 PM	XYL	3.2[C]	0.8	12.7	12.0 X
Day 2 AM	XYL	12.7	3.4	47.7	44.0 X
Day 2 PM	XYL	10.4	4.1	26.5	7.7 X

[A] XYL = xylene, ETB = ethyl benzene, MEK = methyl ethyl ketone, MIK = methyl isobutyl ketone.

[B] X indicates predicted concentration is within statistical range.

[C] At least one sample below limit of detection.

TABLE II. Geometric Mean of Concentrations for Each Analyte at Each Sampling Location and Coefficient of Variations (CV) Pooled for Each Analyte Across All Sampling Locations

Analyte[A]	Quad 1 (mg/m^3)	Quad 2 (mg/m^3)	Quad 3 (mg/m^3)	Quad 4 (mg/m^3)	Pooled CV (%)
ETB	0.84	7.59	4.24	0.73	205
MEK	1.24	7.60	3.83	1.22	141
MIK	1.79	13.44	9.68	1.21	229
XYL	3.31	31.53	17.23	2.15	223

[A] XYL = xylene, ETB = ethyl benzene, MEK = methyl ethyl ketone, MIK = methyl isobutyl ketone.

The analytical results from the area sample experiment are included in Table I. The geometric mean of concentrations for the four areas inside the paint booth, as well as the upper and lower 95% confidence intervals of the geometric mean, are provided. The results for makeup air area samples were below the limit of detection in all cases; therefore, contaminants entering the booth were considered negligible ($C_{in} = 0$). Some of the area samples within the paint booth were below the limit of quantification (LOQ, the lowest accurate quantification standard applied to the gas chromatograph during the analysis). The LOQ in terms of air concentration was 1 mg/m^3. For these samples half the LOQ was substituted for these values to allow for calculation of a geometric mean of the four samples and other relevant statistical description.

As can be seen from Table I, all but two of the predicted concentrations were within the confidence intervals for each analyte. An indication of the spatial variability of the compound concentrations within the room during each sampling period was made by pooling the coefficient of variations (CVs) calculated for each sample period and analyte type as given in Table II. The geometric mean of concentrations for each analyte measured at each sample location is also given in Table II.

Analytical results from the exhaust and personal samples are compared to the predicted concentrations in Table III. Pearson correlation and regression analysis was performed to compare the area, exhaust, and personal sample results to the predicted concentrations (Figures 5, 6, and 7, respectively). Exhaust concentrations had the highest correlation with predicted concentrations (r = 0.923), followed by personal samples (r = 0.828), and area samples (r = 0.757).

DISCUSSION

The k value obtained for the spray booth analyzed in this study was less than 1. Although suggested values for k range from 1 to 10,(12) there are situations where a value of k, calculated from the tracer gas technique, may be less than 1.

TABLE III. Predicted Concentrations Compared to Personal and Exhaust Concentrations for Each Analyte and Sample Day

Analyte[A]	Personal (mg/m^3)	Exhaust (mg/m^3)	Predicted (mg/m^3)
ETB	5.2	6.2	2.9
ETB	2.1	2.3	2.0
ETB	9.8	14.0	7.4
ETB	7.0	7.0	1.3
MEK	5.7	5.3	3.1
MEK	6.4	3.4	1.7
MEK	9.2	6.6	5.9
MEK	8.3	4.9	1.0
MIK	8.2	9.7	6.9
MIK	8.7	6.0	3.7
MIK	16.0	14.0	13.2
MIK	17.0	10.0	2.1
XYL	22.0	28.0	17.2
XYL	9.1	10.0	12.0
XYL	36.0	53.0	44.0
XYL	25.0	27.0	7.7

[A] XYL = xylene, ETB = ethyl benzene, MEK = methyl ethyl ketone, MIK = methyl isobutyl ketone.

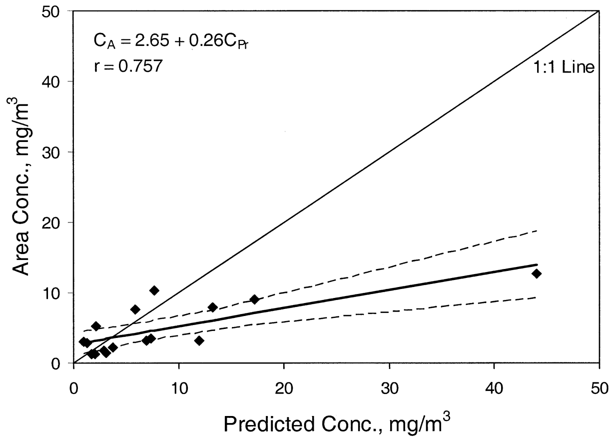

FIGURE 5. Relation between area and predicted concentrations with linear regression line and 95% confidence intervals

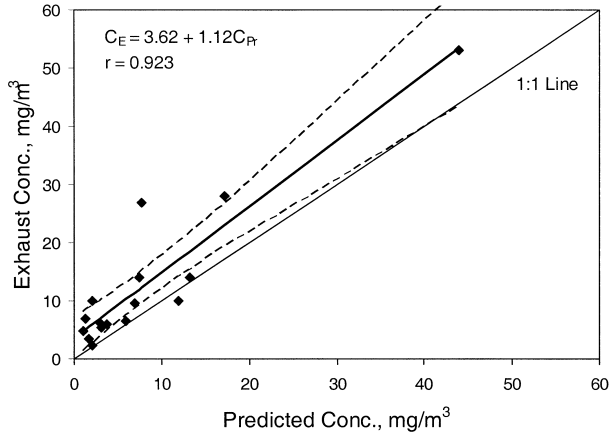

FIGURE 6. Relation between exhaust and predicted concentrations with linear regression line and 95% confidence intervals

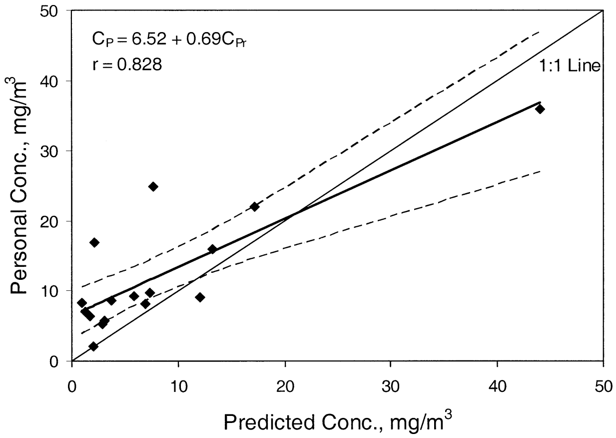

FIGURE 7. Relation between personal and predicted concentrations with linear regression line and 95% confidence intervals

For example, this condition may occur in rooms that exhibit a "tunneling" or "short-circuiting" effect. In that case, air pockets develop in room corners that can be considered "dead space." In effect, this phenomenon reduces the volume of air in the room, which, in turn, causes $Q_{eff} > Q$, and therefore results in a $k < 1$. For the room studied, a very high Reynolds number was obtained, indicating the high turbulence needed to induce complete mixing. However, the presence of flow patterns of various velocities within the room, and the variability in concentrations of analytes throughout the chamber, indicate that there was little back-mixing of the air flowing through the room. This implies that a tunneling effect occurred, which led to a $k < 1$ and the locally high concentrations indicated in Table II.

Likewise, situations may arise in which the value of R in Equation 1 may be significant. In that case, the solution to Equation 1 at steady-state, and for $C_{in} = 0$, results in:

$$C_{eq} = \frac{G}{Q + R}$$

Given this relationship, the nonventilatory losses can be considered to effectively increase the flow rate by an additional amount, R, and, therefore, decrease the resulting concentrations as expected. Under these circumstances a measured value of k will also result in a value less than 1 since R and k are related by $k = Q/(Q + R)$. For the booth studied, the CO_2 used as a tracer gas may have reacted with water vapor and resulted in a significant R value. However, the long-narrow aspect of the room geometry, exceptionally high flowrate through the room, and short residence time would prevent losses of carbon dioxide by reaction to water vapor suggest a tunneling effect in this case.

The large pooled CV values shown in Table II demonstrate the large variability in analyte concentration across the four area sampling locations. This variation is also evident in the large difference between lower and upper confidence limits about the geometric mean for each analyte shown in Table I. As shown in Table II, this variation was due to large differences in concentrations measured at each location with the highest in the upper left. This is consistent with the painting process within the booth. Painting was generally conducted on the left side of the paint booth during this research.

The results of the paint booth sampling area experiments indicate that calculating a concentration based upon mass balance material usage rates appears to be relatively accurate in predicting concentrations within the paint booth. All but two of the predicted concentrations, one each for MEK and MIK, were within the confidence intervals for each analyte. In fact, most predicted concentrations were very close to the geometric mean.

Even with an accurate understanding of the mass balance material usage rate, other unknown variables may contribute to poor model predictability. However, errors in the measurement of the paint used while sampling for MEK and MIK may have contributed to the differences observed between measured concentrations and model results. This could have occurred either before or after the sampling episode when the primer paint was weighed. There could also have been errors during mixing of the paint when the primer paint (Chemlok 205) was mixed with MEK prior to sampling. Due to the small amount of primer paint (and thus MEK and MIK) used during the Day 2 p.m. sampling episode (1.5 lbs), a slight error could have affected the results.

As expected, the strongest correlation between measured concentration and model estimate was obtained for exhaust concentrations. This is no doubt due to the accumulative nature of exhaust ventilation that overrides spatial variability and other confounding variables including human interaction. In addition to the single "tail-pipe" location used to measure these locations, a single location in the center of the room was used to estimate k. This position was apparently representative of the room in general, but weaker correlations with area and personal concentrations suggest, in part, that k varies with position in the booth.

If a tunneling effect did occur in the booth, it is reasonable to assume that k in the main flow field will be lower than in the dead zones located near the booth corners. Therefore, independent estimates of k should be taken for each area of concern within a work environment. Likewise, the observed spatial variation in concentration evident in the room, compounded by the paint sprayer's mobility, contributed to a weaker correlation between personal concentrations and model estimates. Similar results were found by Flynn et al.(14) In addition to the weaker correlation the model estimates were lower than measured personal concentrations for all but two sampling episodes (see Figure 7). Evidently, concentrations were higher than average during the time period when the workers were spraying. Furthermore, the workers were near the contaminant source while spraying and the resulting concentration within their immediate area was higher than that modeled under that assumption of complete mixing throughout the room. In general, a more sophisticated approach to modeling exposures within a specialized volume like a spray booth may be necessary to incorporate, for example, spray transfer efficiency.(13)

CONCLUSION

The trend in modeling for risk assessment is becoming an accepted practice. Industrial hygienists need to become aware of this important tool. The arguments made for modeling are persuasive. Frequent sampling without any modeling of contaminant generation and loss is not efficient. Estimates of exposures can be used to limit the uncertainty and range of possible exposures, and thus allow for proper sample loading on the sampling media. Estimation can also be used to rank risk and prioritize sampling strategies. Targeted sampling can then be used to validate and verify the estimates. Estimation can also be used to select personal protective equipment during sampling or before actual sampling data have been collected and analyzed, or for modeling exposure during design decisions.

Results from this research demonstrate that the mass balance "box model" can be useful for estimating exposures in an industrial setting. However, because of its simplicity relative to an actual ventilated area, model values may differ considerably from measured concentrations. This is especially relevant when attempting to use model results to predict personal exposures. The paint booth used in this research is typical within the industry, and poor spatial mixing, which violates a model assumption, may be expected in similar areas. Likewise, if the mixing is poor and the worker is often located near a contaminant source, then the model may produce liberal estimates of exposure concentration.

Although more sophisticated approaches are available, the use of a box model for estimating exposure concentrations is attractive because of its simplicity. The required analysis of k and calculation of a model estimate can be performed with a spreadsheet. These results indicate that, for volumes similar to the paint booth studied, a k value should be obtained for each area of concern within a room to provide the most accurate match between actual and predicted concentrations. Rooms that exhibit high flow rates and properly placed supply and exhaust vents may exhibit better mixing, in which case a single estimate of k may suffice. Furthermore, the contaminant generation rate does not necessarily have to be steady over time if an estimate of the time-weighted average of potential concentrations is desired. Therefore, the box model can be an important tool in an industrial hygienist's arsenal for understanding actual exposure conditions of a workplace.

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