RESEARCH ARTICLE

Evaluation of a mathematical model for estimating solvent exposures in the workplace

In the context of risk management or occupational exposure assessment, the need often arises to estimate occupational exposures to airborne chemicals. This has traditionally been accomplished by means of air monitoring, however if sufficient information on chemical use plus the physical and environmental factors is available, mathematical models can be used as a means of estimating exposures. Model evaluation, a series of steps through which a model developer or user assesses a model's performance for selected situations,[1] is an important means to understanding the uncertainty associated with a particular model's outcome and to refine the exposure assessment process. This work evaluated the performance of the near field–far field (NF–FF) mathematical model over a range of conditions by comparing predictions made using the model with measured airborne solvent concentrations obtained from two different process evaluations. The first process (*Process #1*) evaluated the application of a penetrating solvent to an iron-body gate valve under three different environmental test conditions. The second process (*Process #2*) was evaluated over a consecutive three-day period during the use of a solvent parts washer for cleaning metal parts. Mean concentration estimates obtained from the modeling process were within a multiplicative range of zero to 1.6 times the arithmetic mean of the actual air sample results from both process evaluations. The general agreement between the predicted and measured concentrations suggests that the construct presented herein sufficiently describes the environmental conditions under which the study was performed. The data provided valuable insight on how the model can predict room concentrations under a range of varied parameters.

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INTRODUCTION

Exposure assessment is a key element of the human health risk assessment process. EPA defines exposure assessment as the "determination or estimation of the magnitude, frequency, duration, and route of exposure."[1] The exposure assessment, like all elements of the risk assessment process, needs to be focused on providing the risk manager with relevant and appropriate information to make a decision with regards to workplace exposure.[2] Estimates of the magnitude of worker exposure are typically made using actual air monitoring data, surrogate data, and more recently, mathematical models.[3] If sufficient information regarding chemical use, as well as relevant physical and environmental factors is available, then mathematical models can be reliably used as a means of estimating exposures.[4] Mathematical modeling may be useful in instances where operations associated with certain exposures have been discontinued, historical air monitoring data are not sufficient or lacking entirely, when prospectively assessing the need for exposure controls, or when limited resources prevent the industrial hygienist from monitoring all operations at all times.[5]

For example, management wants to know if engineering controls will be necessary for controlling solvent vapor emissions following the installation of a degreasing tank that employs a mineral spirits solvent. No air monitoring data is available; therefore the magnitude of likely solvent vapor concentrations is unknown. Using parameters such as vapor generation rate, ventilation rate, and air exchange rate, a mathematical relationship between each parameter can be developed and used to predict the room air concentration of solvent vapors. Furthermore once the model is developed, different input parameters can be considered in order to predict room air concentrations for varying environmental conditions.

The accuracy of a mathematical model remains an important consideration even when sufficient input data are available. Evaluation of a model's performance over a range of input parameters is an important aspect in understanding the uncertainty and limitations associated with a particular model's outcome, and to refine the exposure assessment process.

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[1] ASTM Designation D 5157-97 Standard Guide for Statistical Evaluation of Indoor Air Quality Models, ASTM Committee D-22.05, ASTM, 100 Barr Harbor Drive, West Conshohocken, PA 19428.

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The accuracy of a mathematical model remains an important consideration even when sufficient input data are available.

The objective of this research was to evaluate a mathematical model by comparing predictions made using the model with measured airborne solvent concentrations obtained from two different process evaluations. Different conditions of ventilation were established during each process evaluation in order to examine the model's usefulness over a range of situations. The physical conditions associated with each process evaluation were carefully controlled in order to match, to the extent possible, the parameter inputs for the model.

METHODS

Process #1

Cyclohexane, representing a penetrating solvent, was squirted from a Nalgene laboratory wash bottle onto a 5.08 cm (3″), Class 125 Iron-Body Gate Valve during disassembly of the valve (Plate 1). Process #1 was performed under three different environmental test conditions (i.e., three monitoring periods), each involving a different intensity of air velocity within the test chamber. For statistical considerations, six repetitive trials were performed per test condition.

Each trial was 60 minutes in duration, and the solvent was applied to the valve consistently in order to obtain, to the extent possible, a constant generation rate of solvent vapors. One hundred milliliters of reagent-grade cyclohexane were used for each trial. The MSDS provided by the manufacturer indicated a specific gravity of 0.77, resulting in 77,000 mg of solvent used per trial. The center of the worker's breathing zone was approximately 1 m from the contaminant source.

The work was performed on a bench in the center of a rectangular room measuring approximately 6.33 m long, 5.33 m wide, and 3.35 m high, thus containing a volume of approximately 113 m^3. This room size was selected to represent, based on the authors' professional experience, a small garage, workshop, or engineering space aboard a ship. The room was constructed of nominal 2″ × 4″ (5.08 cm × 10.16 cm) wood framing and 6-mil (0.0254 mm) thick, fire resistive polyethylene sheeting, and was ventilated to facilitate air exchange with the surrounding environment. Ventilation was established by means of a filtered exhaust device placed at one end of the room, and a curtained/flapped entryway with a single-stage airlock located at the opposite end of the room. The design was similar to the concept of the negative-pressure enclosure used for decontamination of potentially hazardous environments. Air movement around and through the breathing zone and contaminant source (conceptual near field) was established using a 40.64 cm diameter variable speed pedestal fan pointed upward at approximately 45° and away from the center of the room.

The selected air velocities included 3.3 m/min. for Test Condition #1, 23 m/min for Test Condition #2, and 61 m/min. for Test Condition #3. Smoke tubes were used to visually observe the air movement around the room, including around the workbench surface and the contaminant source, to verify the air was mixing and was non-directional. Air velocity was measured using a TSI Incorporated Veloci-Check hot wire anemometer. An established air exchange rate of 8.1 m^3/min, equivalent to 4.3 room air changes per hour, nominally, was measured prior to the study following the method described by the American Society for Testing and Materials (ASTM) Method E741-00 "Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution."

During each trial, a personal breathing zone air sample was obtained to measure the mean solvent concentration near the contaminant source and two area air samples were collected to measure the solvent concentration away from the contaminant source but within the room. While the location of the personal air samples was limited to the worker's breathing zone, the area air sample locations were selected in a random manner. A grid was laid out in three dimensions within the room, with each grid being equal to 1 m^3. A computerized random number generator was then used to position two air sampling devices. Grids were automatically disqualified if they were occupied by either the workbench, the location of the worker's breathing zone, or other obstructions.

Plate 1. Cyclohexane being applied to gate valve during Process #1 trials.

Plate 2. The parts washer apparatus used during Study #2. Note air samplers located at the top of the lid (NF zone) and on the tripod stand in the background (FF zone).

The personal breathing zone air samples and the area air samples were obtained over the full 60-minute duration of each trial. MSA Escort Elf low-flow sampling pumps were used for sample collection, and were calibrated before and after each trial using a BIOS Dry-Cal DC-Lite primary gas flow calibrator. The air samples were collected and analyzed in accordance with NIOSH Method 1500 (Hydrocarbons). An independent, American Industrial Hygiene Association (AIHA) accredited laboratory performed the air sample analysis.

Process # 2

A three-day study was conducted to determine the benzene exposure of a worker using a parts washer with a mineral spirits solvent initially containing 0.01% benzene. Parts cleaning activities were performed during two 30-minute sessions each day, one in the morning and one in the afternoon.

The parts washing process involved using petroleum distillate solvents to remove oil, grease and dirt from small metal parts. In brief, a small tank served as a reservoir of liquid solvent. The solvent was pumped from the reservoir tank into a waist-high basin through a scrub brush appliance. The worker scrubbed the part with the brush while the liquid solvent flowed onto the part. The solvent drained through an opening in the bottom surface of the basin and was returned to the reservoir tank (Plate 2). In the past, benzene was present in the cleaning solvent (generally at less than 0.1% weight by weight, w/w), either as a constituent in the fresh solvent supplied to the workplace or present in materials (for example, gasoline) washed from the parts into the apparatus.[5]

The parts washer basin was 86 cm long and 56.5 cm wide (2.81′ × 1.85′), and the 30-gallon reservoir tank held 14 gallons of a hydrotreated petroleum solvent. The solvent density was reported to be in the range 0.77–0.80 g/ml, and consisted of primarily naphthenes and paraffins with 10–14 carbons. The solvent was spiked with benzene to attain an initial concentration of 100 ppm benzene (w/w). Daily bulk sampling of the parts washer solvent revealed that the benzene was lost from the solvent at an exponentially decreasing rate.

The parts washer was located in the center of the rectangular room described above under *Process #1*. Local air movement was established using a pedestal fan to achieve a velocity of 20 feet per minute. A room air exchange rate of four air changes per hour was established, with verification by means of ASTM Method E741-00.

Two fixed position sampling devices were located approximately 61 cm (2′) above the edge of the basin (the conceptual NF) while a defined sequence of cleaning procedures was performed. Two additional fixed-position air samples were placed approximately 2.1 m (7′) to the north and to the south of the parts washer, with charcoal tubes samplers at a height of approximately 1.5 m (5′) above the floor.

The air samples were obtained over two, 240-minute periods, resulting in 8-hours of monitoring each day. MSA Escort Elf low-flow sampling pumps were used for sample collection, and were calibrated before and after each trial using a BIOS Dry-Cal DC-Lite primary gas flow calibrator. The air samples were collected and analyzed in accordance with NIOSH Method 1500 (Hydrocarbons). An independent, American Industrial Hygiene Association (AIHA) accredited laboratory performed the air sample analysis.

The predictive model

The NF–FF model was selected to predict the solvent vapor concentrations since it accounts for spatial variability in exposure intensity,[4] thus representing the concept that exposure intensity is proportional to a person's distance from the vapor source.[6] The NF–FF model, also known as a two-box model, is analogous to a box-inside-of-a-box. The inner box, or NF, is a conceptual fixed space centered on the contaminant source and also contains the worker's breathing zone. The outer box (FF) comprises the remainder of the room. The model is based on the concept of a contaminant mass being emitted over time into the NF where it is then carried to the FF by means of air exchange between the NF and the FF. The exchange of air between the NF and FF is also considered a generation source for the NF, since air in the FF containing the contaminant source is being exchanged with the NF. The contaminant is eventually removed from the room by the airflow from the FF to the outside.[5] This construct also presumes that the air in each zone is well mixed, and that air exchange occurs between each zone. The concept of the model as explained above is

also described by the following mass balance equations for the NF and FF, respectively[7]:

$$V_{NF}\,dC_{NF} = G\,dt + \beta C_{FF}\,dt - \beta C_{NF}\,dt \quad (1)$$

$$V_{FF}\,dC_{FF} = \beta C_{NF}\,dt - [\beta + Q]C_{FF}\,dt \quad (2)$$

where V_{NF} and V_{FF} = the NF and FF volumes, respectively (m^3), C_{NF} and C_{FF} = the NF and FF concentrations, respectively (mg/m^3), G = constant mass emission rate (mg/min), β = interzonal airflow rate (m^3/min) between the NF and FF, Q = room air supply rate (m^3/min), dt = an infinitesimal time interval (min).

Bulk sample measurements taken of the parts washer solvent used in Process #2 indicated the mass emission rate was not constant, but decreased exponentially over time. Therefore the constant mass emission rate (G) described above must be modified to reflect an exponentially decreasing loss rate when modeling the conditions described for Process #2. Exponential loss over time may be described as:

$$G_t = kL_0 e^{-kt} \quad (3)$$

where G_t = mass emission rate at time (t) (mg/min), k = the solvent's evaporation rate constant (min^{-1}), L_0 = the initial liquid solvent mass (mg).

Near field and far field parameters

For Process #1, the NF was represented by a hemisphere with radius (r) = 1 m centered on the contaminant source, and with its base on the workbench. The size of the NF was such that it encompassed not only the contaminant source, but the worker's breathing zone as well. For Process #1 the NF volume was 2.1 m^3. The NF in Process #2 was represented by a rectangular box situated above the parts washer basin. The length and width of the box were equal to the dimensions of the basin, and the NF height was equal to the distance of the air sample media above the lip of the basin. For Process #2 the NF volume was 0.289 m^3.

The FF volume is the difference between the room volume and the NF volume, however in these two cases the NF volume was negligible compared to the room volume. Therefore for Processes #1 and #2 the FF volume equaled the room volume, which in this case was 113 m^3.

The interzonal airflow rate (β) was estimated as the product of one-half the available free surface area (FSA) of the NF and the random air speed (s, m/min) in the vicinity of the NF zone boundary, and is represented below by Eq. (4).[7,8]

$$\beta = \tfrac{1}{2}(\mathrm{FSA}\,s) \quad (4)$$

In the case of Process #1, the base of the hemispherical NF zone was situated on the workbench, thus prohibiting air exchange at this surface. As a result, the base was not included in the FSA calculation. The resulting FSA of the NF zone, based on (r) = 1 m, was 6.28 m^2. For Process #2, both the open lid and basin of the parts washer restricted airflow, resulting in available airflow only through the front, two sides, and top of the NF. Based on the given dimensions of the basin, the FSA of the NF in Process #2 was 1.67 m^2.

As described above in Methods, Process #1, included three test conditions represent three different random air speed values. The selected air speeds included 3.3 m/min. for Test Condition #1, 23 m/min for Test Condition #2, and 61 m/min. for Test Condition #3. Values of air movement intensity were selected to represent conditions of (1) an enclosed area or shop with little ventilation, (2) the same area or shop with open doors/windows and/or people walking in the vicinity, and (3) a well-ventilated or semi-outdoor work environment. Combining each of the selected air speeds with the estimated FSA of the NF, β estimates were 10.4 m^3/min, 23 m^3/min, and 61 m^3/min for Test Conditions #1, #2, and #3, respectively. With a given NF volume of 2.1 m^3, these values represent approximately 1.5, 11.5, and 30.5 air changes per minute for each respective test condition. Each of the three preceding conditions was established based on the authors' personal experience in performing workplace ventilation studies.

Since Eq. (1) includes the C_{FF} as a contributing source to the overall C_{NF}, the volumetric supply/exhaust rate of the room air (Q) is also included in the calculation. The measured air exchange rate for Process #1 was 4.3 air changes per hour, resulting in a Q of 8.1 m^3/min. The measured air exchange rate for Process #2 was 4.0 air changes per hour, resulting in a Q of 7.54 m^3/min.

The mass emission rate (G) for Process #1 was estimated based on 100 ml of reagent-grade cyclohexane being consistently applied to the valve during trial times of 60 minutes each. Constant and steady application of solvent over the duration of each trial prevented pooling of the solvent on the workbench. Situations involving pooling created by spills of solvents are more aptly described by model constructs that incorporate an exponentially decreasing contaminant emission rate.[9] The emission rate decreases as the surface area available for mass transfer decreases and evaporation cools the liquid.[9] With a reported specific gravity of 0.77, the approximate quantity of cyclohexane applied was 77,000 mg. All of the solvent evaporated during the trial time, resulting in a generation rate (G) of (77,000 mg)/(60 minutes) = 1,283.3 mg/min.

For Process #2, daily bulk sampling of the parts washer solvent revealed that the benzene was lost from the solvent at an exponentially decreasing rate. The initial benzene concentration was 100 ppm at $t = 0$, and had decreased to 90 ppm after 4 h. The concentration had decreased to 80 ppm at $t = 24$ h, and after 48 h the concentration was 70 ppm. The first order loss rate α (min^{-1}) of benzene from the solvent has been previously described by Nicas et al.,[5] and can be estimated from the equation:

$$M(t) = M_0 \times e^{(-\alpha t)} \quad (5)$$

where $M(t)$ is the mass remaining at time t (min) and M_0 is the initial mass present at time $t = 0$. The estimate for α during the study period as calculated using Eq. (5) was 4.38×10^{-4}. The initial benzene mass was calculated based on the product of the solvent's volume (14 gallons, or 5.2×10^4 ml), liquid density (770 mg/ml) and ben-

Table 1. The model input parameters for each process evaluation

	Process #1			Process #2		
	Condition 1	Condition 2	Condition 3	Day 1	Day 2	Day 3
G (mg/min)	1,283	1,283	1,283	na	na	na
M_0 (mg)	77,000	77,000	77,000	4107	3286	2875
α (min^{-1})	na	na	na	4.38×10^{-4}	4.38×10^{-4}	4.38×10^{-4}
Q (m^3/min)	8.1	8.1	8.1	7.5	7.5	7.5
β (m^3/min)	10.4	23	61	5.1	5.1	5.1
NF vol. (m^3)	2.1	2.1	2.1	0.29	0.29	0.29
FF vol. (m^3)	113	113	113	113	113	113

zene content (1×10^{-4} w/w), or approximately 4,100 mg.

PREDICTED VERSUS MEASURED CONCENTRATIONS

Each of the input parameters for the model has now been described and is summarized in Table 1 for each process evaluation. The predictions, representing mean cyclohexane concentrations above the workbench and benzene concentrations above the parts washer basin, were numerically computed from the modeled concentration time series derived from Eq. (1) and (2) for the NF and FF, respectively. An example of the model output, showing the predictions for Process #1 – Test Condition #1, and Process #2 – Day 1 are shown in Figures 1 and 2, respectively. Statistical analysis of the air sample data, including calculations of the arithmetic mean, standard deviation, normal and lognormal distribution tests, and confidence interval evaluation was performed using LogNorm2, Statistics for Exposure Assessment (*In Tech Software Corp.*, Tulsa, OK), a PC-based statistical analysis program written specifically for the field of industrial hygiene.

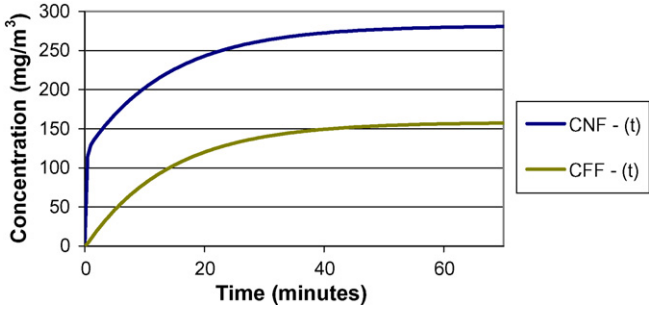

Figure 1. Modeled NF (upper curve) and FF (lower curve) time series concentrations for Process #1 – Test Condition #1. The 480-minute TWA concentration is 243 mg/m³ for the NF and 121 mg/m³ for the FF. The measured 480-minute TWA concentrations were 236 mg/m³ for the NF and 153 mg/m³ for the FF, respectively.

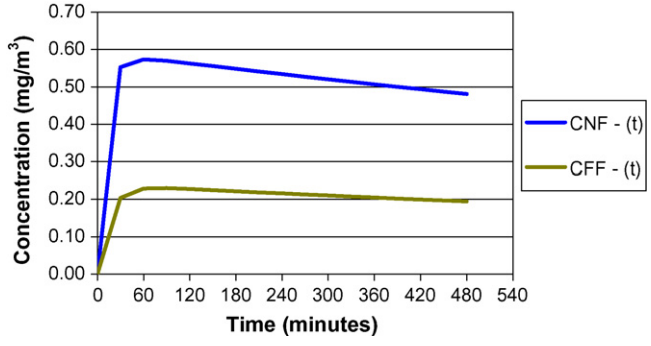

Figure 2. The predicted NF (upper curve) and FF (lower curve) benzene concentrations for Process #2 – Day 1. The 480-minute TWA concentration is 0.50 mg/m³ for the NF and 0.21 mg/m³ for the FF. The measured 480-minute TWA concentrations were 0.50 mg/m³ for the NF and 0.29 mg/m³ for the FF, respectively.

Point concentration estimates obtained from the modeling process were within a multiplicative range of zero to less than two-fold of the arithmetic mean of the actual air sample results obtained from Processes #1 and #2. Table 2 compares the predicted concentrations and the measured concentrations for both Process #1 and Process #2. Graphic representations of the NF predictions versus measured NF concentrations for both Processes #1 and #2 are presented in Figures 3 and 4, respectively.

Results for Process #1

For Process #1 – Test Condition #1, the predicted NF air concentration was 243 mg/m³ and the mean measured NF air concentration, calculated from six Test Condition #1 trials, was 235 mg/m³. The predicted FF air concentration was 121 mg/m³ and the mean measured FF air concentration was 153 mg/m³.

For Process #1 – Test Condition #2, the predicted NF air concentration was 139 mg/m³. The mean measured NF air concentration, calculated from six Test Condition #2 trials, was 137 mg/m³. The predicted FF air concentration was 121 mg/m³, and the measured mean FF air concentration was 153 ppm.

Table 2. Comparison of predicted vs. measured air concentrations for the NF and FF

	Process #1			Process #2		
	Condition 1	Condition 2	Condition 3	Day 1	Day 2	Day 3
C_P NF	243	139	127	0.50	0.40	0.35
C_O NF	236	137	177	0.50	0.24	0.34
C_P FF	121	121	120	0.21	0.16	0.15
C_O FF	153	153	180	0.29	0.15	0.20

All concentrations are expressed in mg/m^3. C_P: predicted concentration in mg/m^3; C_O: measured concentration in mg/m^3.

For Process #1 – Test Condition #3, the predicted NF air concentration was 127 mg/m^3 and the mean measured air sample concentration was 177 mg/m^3. The predicted FF air concentration was 120 mg/m^3 and the mean measured FF air concentration was 180 mg/m^3.

RESULTS FOR PROCESS #2

Since the initial mass (M_0) of benzene present in the parts washer solvent was different at the start of each day ($t = 0$), NF air concentration predictions were made for each day of the three-day study. For Day 1, the predicted NF air concentration was 0.50 mg/m^3. The measured NF air concentration was also 0.50 mg/m^3. The predicted FF air concentration was 0.21 mg/m^3, and the measured FF air concentration was 0.29 mg/m^3. For Day 2, the predicted NF air concentration was 0.40 mg/m^3 and the measured NF air concentration was 0.24 mg/m^3. The predicted FF air concentration was 0.16 mg/m^3, and the measured FF air concentration was 0.15 mg/m^3. For Day 3, the predicted NF air concentration was 0.35 mg/m^3 and the measured air sample concentration was 0.34 mg/m^3. The predicted FF air concentration was 0.15 mg/m^3 and the mean measured FF air concentration was 0.20 mg/m^3.

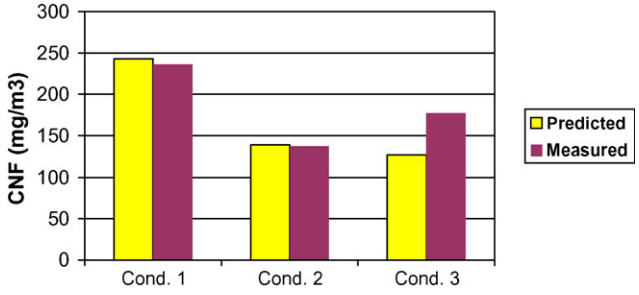

Figure 3. Comparison of predicted NF air concentrations to measured NF air concentrations for Process #1.

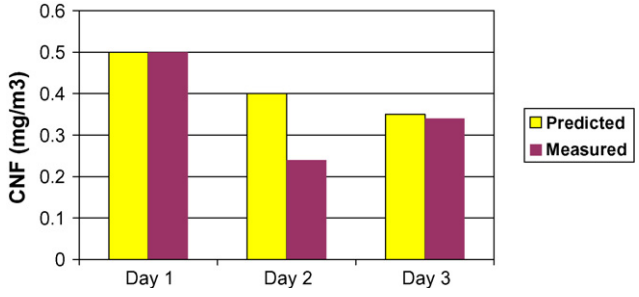

Figure 4. Comparison of predicted NF air concentrations to measured NF air concentrations for Process #2.

DISCUSSION

These results raise two questions concerning the findings. First, did the model construct represent the conditions under study, and second, were there limitations or presumptions inherent in the construct that, if accounted for, may have contributed to closer agreement of predicted versus actual air concentrations?

The NF–FF model adequately accounted for and generally represented the physical conditions established for each process evaluation. Variables including V_{NF}, V_{FF}, and Q, were distinct, measurable parameters whose values did not change over the duration of the study. Uncertainty in the values of the remaining parameters (G, α, and β) contributed the greatest variability to both the modeling predictions and to process evaluation.

Solvent mass emission rates, i.e., evaporation rates, are not hard constants determined by vapor pressure alone. They are also influenced by other factors including but not limited to ambient temperature, atmospheric pressure, air movement above the solvent, the quantity of solvent, and the shape of its container. Therefore, the applied values of G and/or α were specific to this study and may not necessarily be applicable in all modeling situations. Since the authors identified no published values of applicable generation rates for cyclohexane or benzene, G and α were estimated based on real-time observations conducted prior to and during the study.

Calculated loss rates for benzene, based on daily bulk sampling of the parts washer solvent, confirmed that the benzene loss occurred at an exponential rate. The loss rate and associated decay constant was not as

significant as seen in other studies,[5] which reported estimates for α of at least an order of magnitude greater than was used here. Solvent type and/or temperature, usage rate, overall solvent quantity, and test environment may account for the differences.

The interzonal air exchange rate β was estimated based on the FSA of the near field and the measured random air speed (s) around the NF boundary. Since the theory of the NF–FF model is based on random air exchange between the NF and FF zones, the attainment of non-directional air movement within the test chamber was required. This was a challenging endeavor in which considerable time was devoted to ensure that the air movement was behaving in a non-predictable manner, indicating that a degree of randomness had been attained. Measurements of the magnitude of air movement revealed that air movement was not constant, but changing throughout the study process. The uncertainty in determining the actual speed of random air movement was considered when estimating the value for the model input of β.

Uncertainty in modeling, whether in industrial hygiene or otherwise, may be quantified by means of stochastic analysis, an example of which is Monte Carlo simulation. This concept is based on a repeated random sampling from the distribution of values for each of the parameters in a generic equation to derive an estimate of the distribution of exposures in a population.[10] Under the situations described herein, uncertainty in air concentration predictions lay with the solvent generation rate (G) and the random air movement (s) around the NF boundary. Applying Monte Carlo analysis, probability distributions are posed for each of the model inputs to describe their variability over time, and a best estimate of the typical value is used as a distribution parameter of central tendency. The model final estimate reflects the probability distributions from which the model inputs were sampled; distributions are assigned according to the professional judgment of the modelers. The difference between the mean of the Monte Carlo output distribution and the true vapor concentration can be viewed as the bias of the model. The CV of the output distribution measures the precision of the model, such that the smaller the CV (and the more narrow the 95% "confidence" interval), the more precise the estimate.

Limitations, or factors contributing to disagreement between the predicted and measured concentrations were considered. While the design of the study conducted for Process #1 incorporated a constant generation rate G, the true rate of solvent generation during the work practice simulation trials was most likely not entirely constant. Small pools of liquid settling on the work bench, changes in the magnitude of air movement through the NF zone, and imprecision in the constant application of the solvent were contributing factors serving to influence a less than constant rate of vapor generation. In addition, worker movement in the NF zone in Processes #1 and #2 induced additional air mixing/movement not accounted for in the model construct. The effects of convective airflow caused by the worker were also considered, and may have contributed additional uncertainty to the simulation process.

The relatively small size of the test chamber enabled the authors to evaluate the effect of changing the rate of air movement on the airborne concentrations in the NF zone, but also demonstrated confirmation of the principle that where β is much greater than Q, then C_{NF} is approximately equal to C_{FF}, an indication that the room is essentially well mixed. For Process #1 – Test Condition #1, where $\beta < Q$, the ratio of C_{NF}:C_{FF} was 1.5, suggesting fairly well mixed room air, but still exhibiting a significant difference in the measurements. Examination of the results from Process #1 – Test Condition #2 and Test Condition #3, where $\beta \gg Q$, showed comparative NF to FF ratios of 1.1 and 1.0, respectively, indicating that air movement around the room was sufficient to create a well-mixed space.

CONCLUSIONS

Health and safety professionals have traditionally relied on the results of exposure monitoring to characterize and group workers having similar exposure profiles, or to make decisions concerning the use of exposure controls. Modeling may be a useful alternative to air monitoring in some cases, especially when no representative data is available or when limited resources preclude the monitoring of all tasks or situations. Additionally, modeling data can serve as a leading indicator of potential overexposure, whereas the results of traditional air monitoring are often not known until after the exposure has occurred.

Mathematical models also allow us to examine the factors that influence the exposure itself. For example, how would solvent vapor concentrations generated during a particular process be affected if we changed the rate of air airflow around the worker, changed the room air exchange rate, or applied the solvent in a more controlled fashion? Examining these factors enables the risk assessor to select more appropriate input parameters or make better-informed decisions for exposure control.

Mathematical models also allow us to examine the factors that influence the exposure itself.

Although there was general agreement between the predicted and measured results (within a multiplicative range of zero to 1.6), the model underestimated the mean measured concentration in half of the situations evaluated. This suggests that some of our input parameters may not have been conservative enough to provide a worst-case concentration estimate, which is often desired in order to guard against underestimation.[2]

The general agreement between the predicted and measured concentrations suggests that this construct sufficiently describes the emission and dispersion around the valve and parts washer, and within the room. The data provided valuable insight on how the

model can predict room air concentrations under a range of specified parameters. Refinement of input parameters and the use of stochastic analysis would most likely prove beneficial for evaluating the range of exposure potential under similar situations.

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