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Empirical–conceptual models relate exposure to various process parameters responsible for the generation and transport of airborne contaminants. If the model includes all process parameters important to defining the exposure, it has the potential for *a priori* exposure prediction. This research tested the ability of an empirical–conceptual model of a spray painting task to predict worker exposures in the field. The model relates paint mist concentrations to spray booth ventilation rates and other process parameters, including spray gun nozzle pressure, paint viscosity, mist generation rates, and worker orientation to the booth freestream. Eight workers in a paint shop were sampled over a 5-week period. A total of 55 tasks were sampled; 40 percent of the measured task exposures are within the estimated experimental error of the model prediction and 71 percent are within a factor of three. Excluding tasks that either did not fit the model assumptions well or where a sampling error may have occurred increases the percentage to 84 percent within a factor of three. Four of the eight worker mean exposures are within one standard error of the model prediction. These positive results indicate that empirical–conceptual models can predict exposure and also aid in the design and economic optimization of engineering controls. CARLTON, G.N.; FLYNN, M.R.: FIELD EVALUATION OF AN EMPIRICAL–CONCEPTUAL EXPOSURE MODEL. APPL. OCCUP. ENVIRON. HYG. 12(8):555–561; 1997. © 1997 AIH.

The importance of engineering controls is self-evident to an industrial hygienist. For inhalation hazards the benefits of a control measure such as ventilation include capture of the contaminant and a reduction in the worker's exposure. Although exposure is related to ventilation, the form of this relationship is seldom known for a specific industrial operation due to variable process parameters. A successful exposure model would describe the relationship between these parameters, the ventilation rate, and the exposure.

Previous attempts to model worker exposures were done either as part of retrospective exposure assessments for epidemiological purposes[1–4] or to identify factors that could influence exposure.[5–8] These studies associated the measured exposure to various process parameters statistically and therefore are known as empirical–statistical models. The ability of these *a posteriori* models to predict an exposure *a priori*, however, is unknown. In addition, the assumption of linearity implicit in statistical regression analysis can obscure the functional relationship among exposure, ventilation, and process parameters. As a result, application of these models to engineering control designs is difficult.

A different modeling technique which may have wider applicability than the statistical approach is the so-called empirical–conceptual model. These models relate the exposure to the ventilation and process parameters using a more deterministic approach. A conceptual model depicts contaminant generation and transport processes leading to the exposure. An examination of these processes identifies important parameters that characterize the industrial operation. Once these parameters are known, they are grouped into nondimensional ratios using the technique of dimensional analysis. Experiments are then performed to determine the functional relationship among these ratios. Empirical–conceptual models improve physical insight into a problem and, most important to an industrial hygienist, can potentially be generalized to new situations.[9] As long as a sound conceptual understanding of the industrial operation exists, the model should include all process parameters important to defining the exposure. These models raise the prospect for *a priori* application and economic optimization of control.

In a previous article[10] the authors developed an empirical–conceptual model of a compressed air spray painting task. Such tasks take place in ventilated spray booths. The model related the breathing zone concentration of paint mist to the ventilation rate and certain process parameters believed to influence the generation and transport of the paint mist into the breathing zone. The purpose of this article is to test the model in the field and determine its ability to predict worker exposures *a priori*.

Description of the Model

Model Development

A short summary of the model development follows. A more complete description can be found in the original article.[10] A worker's exposure to paint mist results from three processes common to all compressed air painting tasks: droplet formation, droplet transfer, and droplet transport.

Droplet formation results when a spray gun causes compressed air to atomize paint and form droplets. Researchers have shown empirically that the important factors influencing the resulting droplet size distributions are air pressure at the spray gun nozzle (p_n), liquid paint viscosity (μ_l), and the ratio of air to liquid mass flow rates (m_a/m_l).[11–13]

Droplet transfer creates the paint mist or overspray generation rate (m_o) (g/s) that fails to coat the workpiece. The

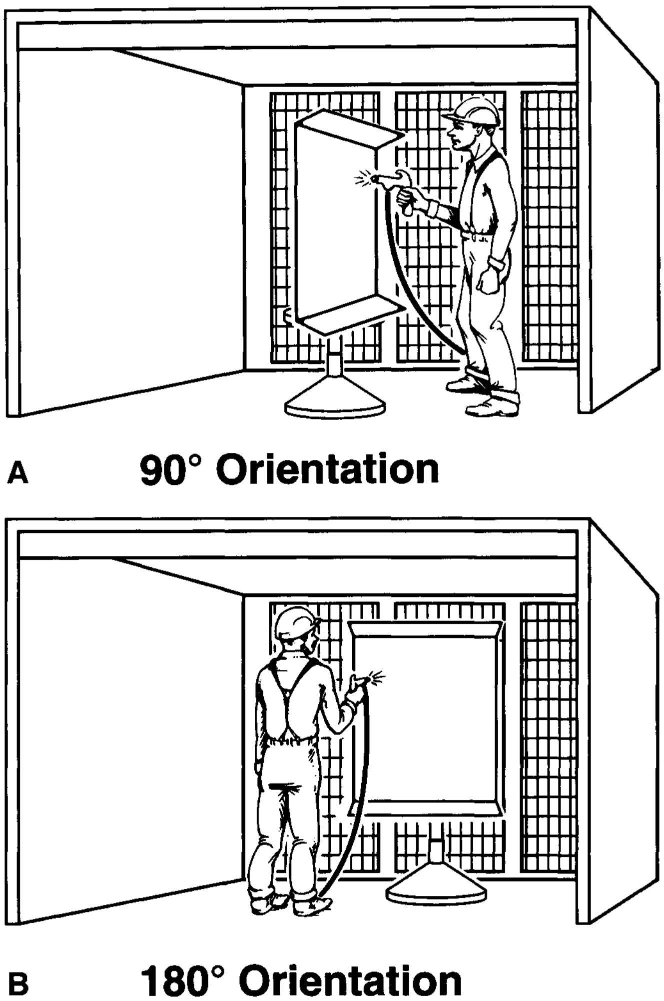

FIGURE 1. Worker orientation to the freestream. In the 90° orientation (A) the freestream flows to the worker's side; in the 180° orientation (B), to the worker's back.

transfer efficiency of the spray (i.e., the fraction of droplets that impact on the workpiece) primarily depends on droplet momentum and spray gun to workpiece distance. The model assumes this distance is constant at 8 inches, per industry recommendations.(14) Droplet momentum is a function of the droplet size and velocity, both of which are related to the nozzle pressure.

Droplet transport moves the overspray from the workpiece into the worker's breathing zone. This transport depends on the freestream velocity in the spray booth (U). In addition, empirical observations indicate that both worker orientation to the freestream and the worker size (height H and breadth D) may influence droplet transport.(15–18) During spray painting tasks, the worker generally orients the workpiece so the freestream is either to the worker's side (90° orientation) or to the back (180° orientation; see Figure 1).

The primary hypothesis is that the worker's average breathing zone concentration (C) is a function (ϕ) of the process factors identified in the conceptual model presented above. Representing the dependence as an equation,

$$C = \phi\left(m_o, p_n, \mu_l, \frac{m_a}{m_l}, U, H, D, \text{orientation}\right) \tag{1}$$

Dimensional analysis provides the following dimensionless representation of the model:

$$\frac{CUHD}{m_o} = \Phi\left(\frac{m_a}{m_l}, \frac{p_n H}{\mu_l U}, \text{orientation}\right) \tag{2}$$

The model indicates that the concentration group $CUHD/m_o$ depends on worker orientation to the freestream and two other nondimensional groups: the air to liquid mass flow ratio m_a/m_l and the pressure group p_nH/μ_lU.

A laboratory setup of a mannequin, flat plate, and spray nozzle in a wind tunnel was used to determine the functional relationship between these quantities, which is shown in Figure 2. The model indicates that $CUHD/m_o$ is a strong function of the quantity p_nH/μ_lU and worker orientation. The air to liquid mass flow ratio was not a significant factor in either orientation.

Further Considerations

The original article(10) discussed the importance of worker orientation and suggested several reasons for the orientation effect illustrated in Figure 2. It did not, however, address why the pressure group p_nH/μ_lU is an important factor in the resulting exposure. It is also unclear why m_a/m_l is not. Some further considerations help to clarify these issues.

At first glance the significance of p_nH/μ_lU, a grouping of nozzle pressure, liquid viscosity, freestream velocity, and the scaling factor of worker height, appears obscure. The relationship among these quantities can be rewritten as

$$\frac{p_n H}{\mu_l U} = \frac{H/U}{\mu_l/p_n} \tag{3}$$

Both H/U and μ_l/p_n have units of time; therefore, p_nH/μ_lU is actually the ratio of two time scales:

$$\frac{p_n H}{\mu_l U} = \frac{\tau_1}{\tau_2} \tag{4}$$

The ratio of the characteristic model length (i.e., worker

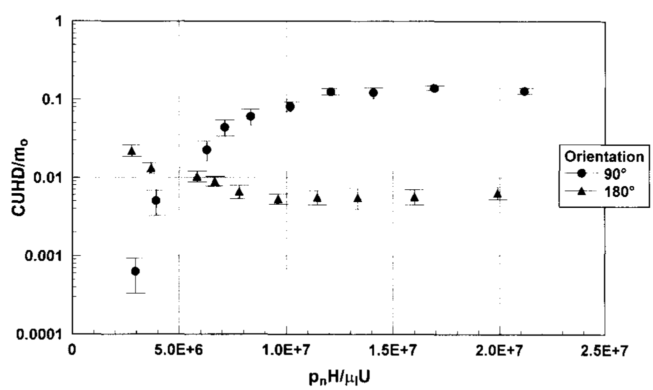

FIGURE 2. Empirical–conceptual model of a spray painting task showing the functional relationship between the important dimensionless groups.

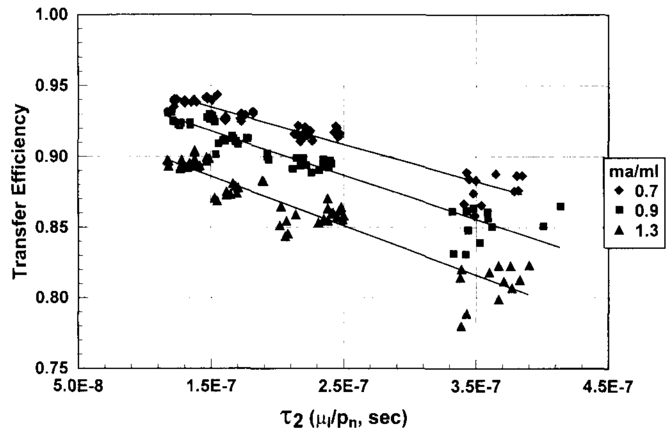

FIGURE 3. The relation between spray transfer efficiency and the spray nozzle parameters μ_l/p_n and m_a/m_l for the Spraying Systems 1/4J nozzle.

height) to the average freestream velocity is τ_1. It represents a measure of the residence time of overspray droplets in the vicinity of the painting task. Higher residence times correspond to a greater chance for the droplets to enter and remain in the breathing zone. Therefore, τ_1 is a measure of the potential for the overspray droplets, once formed, to result in exposure.

The ratio of paint viscosity to spray gun nozzle pressure is τ_2. While the atomization process is complicated (especially with a non-Newtonian fluid such as paint), p_n and μ_l influence the droplet size distribution created by the spray nozzle.[11–13] Therefore, τ_2 should influence droplet transfer to the workpiece and the resulting overspray generation rate. In fact, since the velocity of the exiting air jet is essentially sonic at all nozzle pressures greater than 20 psig,[19] and the model assumes a constant spray gun to workpiece distance, droplet size is the most important factor influencing transfer efficiency. Therefore, τ_2 is a measure of the transfer efficiency of the spraying task. Figure 3 graphs the measured transfer efficiencies, as a function of τ_2 and m_a/m_l, for the 180 data points used to generate the model curves in Figure 2. A strong correlation between transfer efficiency and τ_2 is evident; r^2 equals 0.903, 0.901, and 0.872 for m_a/m_l values of 0.70, 0.90, and 1.30, respectively.

The quantity p_nH/μ_lU incorporates the relative contributions of the droplet transfer and transport processes in producing an exposure:

$$\frac{p_n H}{\mu_l U} = \frac{\text{droplet transport}}{\text{droplet transfer}} \quad (5)$$

Therein lies its importance to spray painting. The quantity m_a/m_l, however, is also an important factor in the transfer efficiency of the task, as indicated in Figure 3, where the fitted lines are noncoincident per dummy variable regression,[20] $p \ll 0.0001$. The factor m_a/m_l fails to enter the final model because the conceptual model related the breathing zone concentration to the overspray generation rate, not the transfer efficiency. As a result, the quantity m_a/m_l, which influences the transfer process but not the transport process, did not appear in the analysis. Using m_o to normalize the concentration group $CUHD/m_o$ considerably simplifies the model and allows its application to spray nozzles which exhibit transfer efficiencies different from those indicated in Figure 3.

Methods

Field sampling took place at the component repair paint shop of Robins Air Force Base, Warner-Robins, Georgia. Robins Air Force Base is a U.S. Air Force logistics base performing depot level maintenance of C-141 and C-130 transport aircraft and F-15 fighter aircraft. Component parts are removed from the aircraft for necessary repairs. Prior to reinstallation on the aircraft, the repaired components are primed and painted in the paint shop. Typical components painted include F-15 stabilizers and bomb racks, C-141 and C-130 wing flaps, and C-141 pylons.

The paint shop uses three spray booths of different sizes. The smallest measures 17.9 ft wide by 9.5 ft high by 29.8 ft deep. The largest measures 33.9 by 13.6 by 32.7 ft. Each booth has a water curtain to remove captured overspray in the exhaust. Workers prime with either an epoxy or a high solids polyurethane primer, depending on the aircraft component. The paint used is a high solids polyurethane enamel thinned with a solvent thinner. Workers use a DeVilbiss conventional spray gun, model MBC-510-30EX, in siphon feed cup configuration.

The field study followed eight workers over a 5-week period. A total of 55 spray painting tasks were sampled. Tasks were selected that best fit the assumptions of the model: the workpiece could be represented as a flat plate and its size was on the order of the worker's height. All tasks were videotaped. The tapes were later viewed to determine the task time (t_{task}), spray time (t_{spray}), time spent spraying in the 90° orientation (t_{90}), and spraying time in the 180° orientation (t_{180}).

Task Exposure

Polyvinylchloride membrane filters (5-μm pore size in 37-mm cassettes) were placed in the worker's breathing zone and sampled at 2.0 L/min to measure total aerosol mass.[21] To simulate the characteristics of the inhalable mass sampler,[22] a 25-mm hole was drilled in the cap of the cassette. The filter cassette was attached to the worker's lapel with a holder designed to keep the face of the cassette parallel to the worker's body. To measure solvent that evaporated from the collected droplets during sampling, two large charcoal tubes in parallel backed up the filter cassettes. The filters were weighed before and after sampling on a Cahn model 27 electrobalance with 0.001-mg sensitivity. An American Industrial Hygiene Association-accredited lab analyzed the charcoal tubes using National Institute for Occupational Safety and Health Method 1550 for total hydrocarbons.[23] The task exposure was calculated from the sum of the collected solids and solvent, sampling rate, and task time.

Measurement of Task Parameters

A pressure tap was installed in a DeVilbiss model 30 air cap. After each spraying task, the air cap on the worker's gun was replaced with the modified air cap to measure the nozzle pressure. Paint viscosity was measured during each task with a Zahn #2 viscosity cup. Spray booth face velocities were measured with a calibrated Alnor® model 8565 thermoanemometer. Worker height and breadth were measured with a tape measure.

Overspray Generation Rate

The transfer efficiency of the DeVilbiss spray gun was measured directly. One siphon cup of high solids enamel thinned to 17 seconds Zahn cup #2 (15 centipoise, the average viscosity of the paint used) was sprayed onto a flat plate with the back-and-forth motion and fan spray pattern used by the painters. Paint that impacted on the plate drained into a trough located beneath it. The difference in trough weight before and after spraying was the mass of paint transferred to the plate. The transfer efficiency was the fraction of the sprayed mass that impacted the plate. This procedure was repeated for nozzle pressures from 50 to 90 psig, the range encountered during the field studies. Transfer efficiencies ranged from 0.78 at 50 psig (SD = 0.006) to 0.68 at 90 psig (SD = 0.009).

During each spraying task, the siphon cup was weighed before and after spraying. The difference was the amount sprayed from the cup. The total mass sprayed was the sum of these differences for all cups sprayed during the task. The overspray generation rate was estimated from the measured transfer efficiency at the nozzle pressure used:

$$m_o = (1 - \mathrm{TE}) \times \left(\frac{\text{mass sprayed}}{t_{spray}}\right) \tag{6}$$

Calculation of Predicted Exposure

The average breathing zone concentration predicted by the model (C_{model}) was weighted for the time the worker actually sprayed:

$$C_{model} = \frac{(C_{spray}t_{spray} + C_{off}t_{off})}{t_{task}} \tag{7}$$

where total task time $t_{task} = t_{spray} + t_{off}$. Assuming the worker received an exposure only when spraying, $C_{off} = 0$. Similarly, C_{spray} was calculated as the concentration predicted by the model weighted for the times the worker spent in the two orientations:

$$C_{spray} = \frac{(C_{90}t_{90} + C_{180}t_{180})}{t_{spray}} \tag{8}$$

where C_{90} and C_{180} were found from the measured task parameters, calculated overspray generation rate, and Figure 2. Combining Equations 7 and 8,

$$C_{model} = \frac{(C_{90}t_{90} + C_{180}t_{180})}{t_{task}} \tag{9}$$

For most of the spraying tasks, p_nH/μ_lU exceeded 2.0×10^7, placing the tasks in an area to the right of the model curves shown in Figure 2. To calculate C_{90} and C_{180} in these cases, it was assumed the curves had reached asymptotic values of 0.134 in the 90° orientation and 0.006 in the 180° orientation.

Results

The total worker exposure distribution is shown in Figure 4. Individual task exposures range from 7.7 to 568.6 mg/m³. The group geometric mean exposure is 86.4 mg/m³, with worker mean exposures varying from 40.4 to 235.2 mg/m³. The individual task exposures are well characterized by a lognormal distribution, as illustrated in Figure 5. A goodness-of-fit to the lognormal distribution using the Shapiro-Wilk test of normality on the log-transformed exposures indicates that the hypothesis of lognormality is not rejected at the 0.05 level of significance ($p = 0.31$).

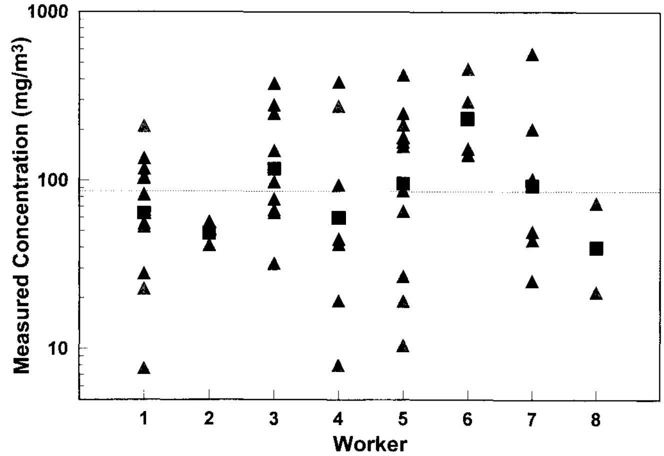

FIGURE 4. Total worker exposure distribution. Triangles represent individual tasks; squares the worker geometric mean exposure; dashed line the overall group exposure.

Calculated values of the dimensionless concentration group, $CUHD/m_o$, are graphed versus the pressure group, p_nH/μ_lU, in Figure 6. Forty-nine values (89% of the data) fall within the asymptotic limits of the model. Of the six values that fall outside the model limits, five are above the 90° orientation limit.

The predictive ability of the model is shown in Figure 7. Measured task exposures were on average less than that predicted by the model; 32 task exposures (58%) were less than the model prediction. Twenty-two tasks (40%) fall within the estimated experimental error of the model prediction, based on

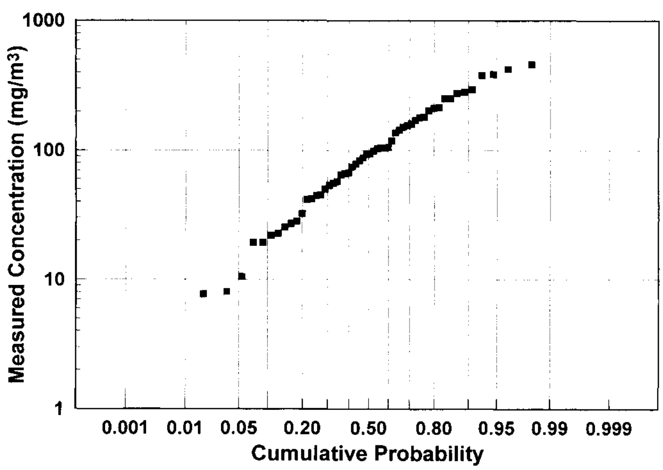

FIGURE 5. Graphic goodness-of-fit of the worker exposures to the lognormal distribution.

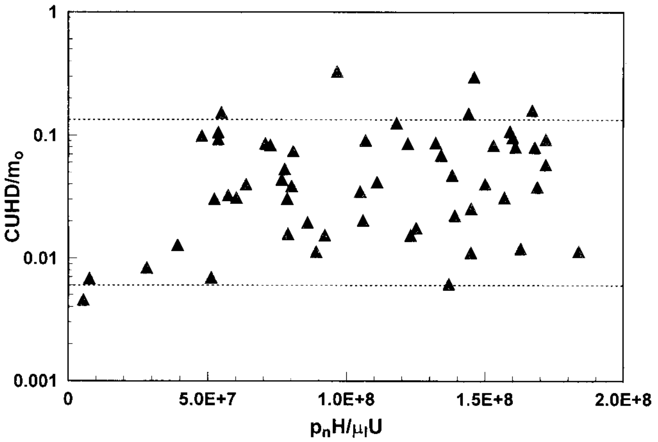

FIGURE 6. Individual task CUHD/m_o values graphed as a function of the pressure group p_nH/μ_lU. Dashed lines represent asymptotic values of the model in the 90° and 180° orientations.

the measurement uncertainty of the task parameters and the overspray generation rate.[24] Thirty-nine task exposures (71%) are within a factor of three of the model prediction.

A Wilcoxon signed-rank test compared the differences between the measured exposures and the model predictions. This test was used instead of a paired *t*-test because the pairwise differences are not normally distributed. The signed-rank test indicates that the hypothesis of no difference between measured and predicted exposures is not rejected at the 0.05 level of significance ($p = 0.91$). Regression of measured exposures on those predicted by the model gives a similar conclusion. Using either a linear regression (slope = 0.87, not significantly different from one; intercept not significantly different from zero) or a weighted regression with t_{task} as the weighting factor (slope = 0.96, not significantly different from one; intercept not significantly different from zero) results in the conclusion that the regression line is not significantly different from the line of equivalence in Figure 7.

The predicted and measured mean worker exposures, as well as the overall group exposure during the course of the field study, are shown in Figure 8. Error bars indicate one

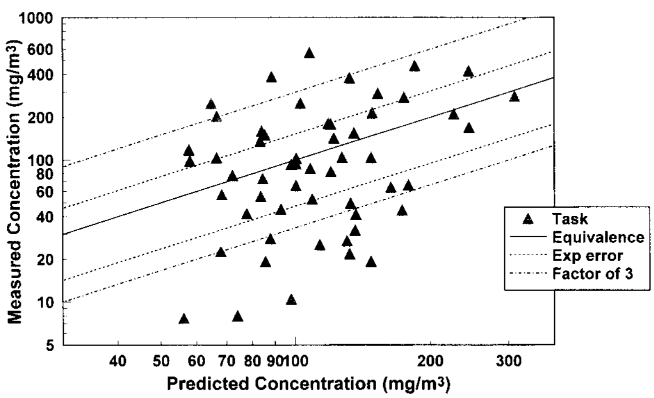

FIGURE 7. Scatter plot of measured worker task exposures and model predictions. The majority of the data lie within a factor of three of the model line.

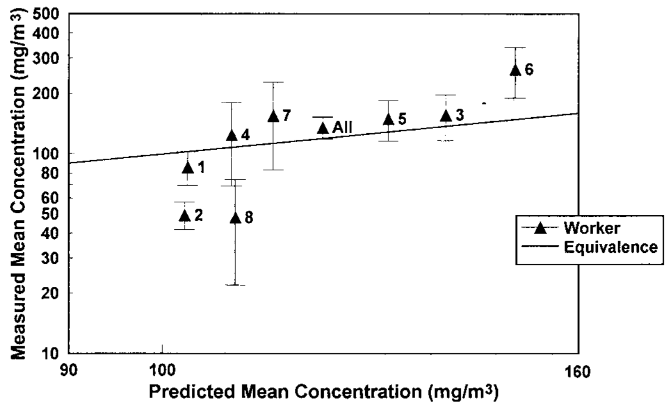

FIGURE 8. Measured mean worker exposures for the field study and the associated model predictions. Most of the predictions are within one standard error of the mean.

standard error of the mean. Four of the eight workers' mean exposures are within one standard error of the model prediction. Significantly, these four workers were among the five on whom the most samples were taken (workers 1, 3, 4, 5, and 7).

Discussion

Considering the simplicity of the model and mitigating factors present in actual field settings, the agreement between predicted and measured exposures is encouraging. The majority of individual task exposures are within a factor of three of the model prediction, persuasive in a model based solely on the dimensional relationship of the task parameters and not on any physical law. Although measured exposures tended to be less than those predicted by the model, statistical analysis indicates that this trend was not significant. The ability of the model to predict worker mean exposures, illustrated in Figure 8, is good.

The extreme values in Figure 7—those that lie outside a factor of three from the model prediction—beg the question of why the model did not do a better job for these tasks. To address this, task videos were viewed again and sampling results reviewed to identify other factors, not accounted for in the model, that may have affected the worker exposure.

All workers had a cart where they mixed paint prior to starting the painting task. On occasion, the workers mixed additional paint during the task if they misjudged the amount required. Sometimes the workers had to clean dried paint from the gun air cap by dipping the cap in a solvent tank located on the cart. This cleaning procedure could contribute additional solvent exposure above that predicted by the model. Of the 15 tasks identified where the worker either mixed or cleaned during the task, nine exposures are greater than the model prediction, and of these nine, two are more than a factor of three different. However, six are below the model prediction. This possible additional exposure does not appear to explain the outliers, but it could have contributed to the overall tendency of these tasks to exceed the model predictions.

As mentioned previously, painting tasks were sampled when a flat plate could represent the workpiece, ensuring that the overspray generation and transport characteristics were similar to the laboratory setup. Four of the tasks involved painting an air intake for the F-15 engine. This component has flat sur-

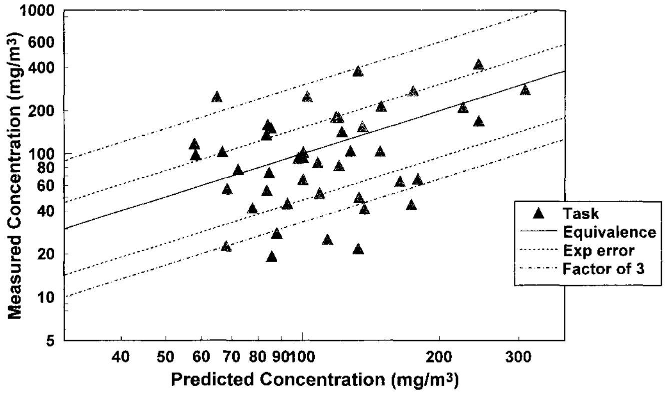

FIGURE 9. Revised scatter plot of Figure 7, with possible anomalous task exposures removed.

faces, but on one side has two end fins that form a 90° angle with the flat surface. Painting this surface requires the painter to stand between the two end fins. This positioning causes the overspray to channel directly toward the worker and not in the wrap-around pattern normally seen in the 90° orientation.[10,25] The measured exposures for three of these four tasks are more than a factor of three greater than the model prediction. The shape of the workpiece appears to have contributed to this difference.

Review of the charcoal tube analyses indicates no solvent exposure for six of the tasks. Considering that all other tasks had detectable solvent levels, this was unusual. These six tasks were sampled sequentially over a 3-day period on different workers. The charcoal tubes were sent for analysis in a mailing separate from most of the other samples. These facts lead to a suspicion that a sampling, shipment, or analysis error occurred. All of these six tasks are more than a factor of three less than the model prediction. In addition, during one task the worker dripped some primer onto the cassette holder and filter. His task exposure is more than a factor of three over the model prediction.

Removing these 11 possibly anomalous samples from the total distribution results in the revised scatter plot in Figure 9. In the revised data set, 84 percent of the tasks fall within a factor of three of the model prediction. Ninety-five percent of CUHD/m_o values fall within the asymptotic model limits. A Wilcoxon signed-rank test on the revised data set leads to the previous conclusion, that is, no statistical difference between the measured and predicted exposures ($p = 0.65$). Regression analysis also results in the same conclusion as before (regression line and line of equivalence are not significantly different). The predicted and measured mean exposures in Figure 8 shift slightly in the revised data set, most notably for workers 6 and 7 (points shifted down), but the overall predictive ability of the model is not changed appreciably.

The original article[10] identified several limitations that could affect the predictive ability of the model, and for the most part these limitations were borne out in the field. Movement of workers and their spray guns, plus the tendency for the spray pattern to miss the object when painting the edge of a workpiece, produced overspray generation rates that were probably higher than predicted by Equation 6. The model assumes a fixed spray gun-to-workpiece distance of 8 inches, but depending on the size of the workpiece this distance would increase if the worker could not reach far enough. This increase in distance tends to increase the overspray generation rate, although this effect is probably balanced by a decreased chance of overspray transport back to the worker due to the greater distance. The model assumes a workpiece parallel to the worker's body, but in actuality the workpiece could be at an angle, thereby diverting the overspray away from the worker. In these cases, actual overspray motion may have differed from that used to develop the model.

In the development of the model an aerosol of low volatility (corn oil) was used. In actual spray painting operations the paint droplets will evaporate and transfer some of the mass into the vapor phase prior to any type of personal sampling. An important assumption in the development of the model was that, to a first approximation, this evaporated vapor would be transported much like the aerosol. Thus the model, which predicts a total mass exposure, should be applicable to a volatile aerosol as long as both vapor and aerosol are sampled, regardless of whether the evaporation occurs before or after sampling. This is a limiting approximation, but given the uncertainties of simulating real-world applications, perhaps a reasonable one.

Conclusions

The authors believe the positive results of this initial *a priori* application of an empirical–conceptual model are sufficiently encouraging to support additional work into the modeling technique. This research indicates that empirical–conceptual models have the potential to predict individual worker task exposures within a factor of three and mean exposures within one standard error of the mean. Future exposure models for spray painting should continue to address the real-world complexities, some of which are highlighted above and which are ultimately concerned with better estimates of transfer efficiency and an improved knowledge of overspray transport mechanisms. It is also important to account for other tasks that may occur coincident with spraying, most importantly additional solvent exposure from mixing and cleaning. These improved models could have wider applicability than the current model and lead to improved exposure control methods.

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