Revisiting the Effect of Room Size and General Ventilation on the Relationship between Near- and Far-Field Air Concentrations

JOHN W. CHERRIE1*, LAURA MACCALMAN1, WOUTER FRANSMAN2, ERIK TIELEMANS2, MARTIN TISCHER3 and MARTIE VAN TONGEREN1

1Institute of Occupational Medicine, Research Avenue North, Edinburgh EH14 4AP, UK; 2TNO Quality of Life, The Netherlands, PO Box 360, 3700 AJ Zeist, The Netherlands; 3Federal Institute for Occupational Safety and Health (BAuA), Friedrich-Henkel-Weg 1-25, D-44149 Dortmund, Germany

Received 13 October 2010; in final form 6 September 2011

Objectives: In 1999, Cherrie carried out a series of mathematical simulations to investigate dispersion of pollutants through two indoor zones: the near-field (NF) and the far-field (FF). The results of these simulations were used to derive modifying factors for use in exposure modeling. However, in the original simulations, no account was taken of deposition on surfaces, either from sedimentation of aerosols or other mechanisms or the potential effects of intermittent or short duration sources. These factors may affect pollutant dispersion, particularly the relationship between NF and FF levels. The Advanced REACH Tool (ART) is based on a two-zone dispersion paradigm. Further simulations have been carried out to help ensure that the ART realistically reflects pollutant dispersion.

Methods: Pollutant dispersion has been simulated using a two-compartment well-mixed box model to represent the NF and the FF. Simulations were repeated for a range of room sizes and ventilation conditions. Intermittent sources (e.g. batch processes) were simulated by having the source active for 1 h followed by a 1-h gap, while short duration work emissions were set to last for 10 min, 30 min, 1 h, or 4 h, within the working day. Deposition was modeled by adding an equivalent air exchange rate based on published research data. Simulations were undertaken for non-volatile, monodisperse aerosols of aerodynamic diameter: 0.3, 1, 3, 10, 30, and 100 μm and the results were then interpreted in terms of typical polydisperse industrial aerosols.

Results: Room size and general ventilation strongly influenced dispersion from the NF to the FF as Cherrie had originally found. When varying the duration of the simulation, the biggest difference from continuous work was seen in small poorly ventilated rooms, with the ratio of the NF to FF concentration for 1-h work in the smallest room and lowest air exchange rate being a fifth of that calculated for continuous work. For large rooms and high general ventilation rates, the duration of the activity made little difference to dispersion. The results suggest that for the purposes of dispersion intermittent batch work is equivalent to continuous work. For typical simulated poly-disperse aerosols, the main effect of aerosol deposition was to reduce the predicted high concentrations compared to vapours when working in confined spaces.

Conclusions: Both short duration of source emissions and deposition of aerosols have an important effect on dispersion, and the results from this study have been reflected in the ART model.

Keywords: ART; reach; Advanced REACH Tool; exposure assessment; exposure model; dispersion; far-field; general ventilation; modelling; near-field

INTRODUCTION

Inside a building, the dispersion of airborne substances may be a complex process determined by
turbulent diffusion, bulk airflow, and other processes. The quantity of general ventilation and the volume of a room have an important impact on the concentration of a contaminant in the air. The relationship can be modeled mathematically using a simple differential equation. By subdividing a room volume into a number of discrete interconnected well-mixed compartments, it is possible to model the variation in contaminant concentration within a larger room with a number of simultaneous differential equations and gain some insight into the dispersion of airborne substances away from a source.

Cherrie (1999) investigated the dispersion of a gaseous air contaminant using a two-compartment model, where a virtual cube of side 2 m was located around the workers nose and mouth [designated the near-field (NF)] and a second box that comprised the remainder of the room [designated the far-field (FF)]. With this very simple abstraction, he found that the ratio of the NF to FF concentration ranged from unity in small poorly ventilated rooms to 24 in large well-ventilated spaces. A similar pattern was seen with occupational air monitoring data when the ratio of personal to static sample concentration data from the same work environments was calculated. The data from Cherrie’s simulations were used to make recommendations about modifying modeled exposure estimates for different room sizes and general ventilation rates, depending on whether sources were located in the NF or FF (Cherrie and Schneider, 1999; Semple et al., 2001). This approach has subsequently been used as part of a modeling framework to retrospectively estimate inhalation exposure for a number of epidemiological and other research studies (Seaton and Cherrie, 1998; Kjaerheim et al., 2002; Boffetta et al., 2004; Cherrie et al., 2009).

The approach described by Cherrie and Schneider (1999) has been used as the basis for a new exposure modeling tool for use with the European REACH Regulations—the Advanced REACH Tool (ART, Tielemans et al., 2011). As part of this development, we have revisited the original simulation work and extended these to provide a more comprehensive basis for recommending how contaminant dispersion should be modeled. In particular, we have explored the effect of continuous versus intermittent work patterns and the effect of including surface deposition of aerosols to understand whether there are important differences in dispersion between aerosols and gases or vapours.

**METHODS**

**Modeling dispersion**

The approach taken by Cherrie (1999), and in the conceptual model developed for indoor dispersion in the ART model, was to divide the workspace into two well-mixed compartments: the NF centred on the worker and the FF comprising the remainder of the indoor space. This can be described by two simultaneous first-order differential equations representing the exchange of contaminant mass between the compartments, including mass lost from the system. For example, the following equations describe this type of model where the source is located in the NF:

\[
V_{NF} \frac{dC_{NF}}{dt} = e_T - C_{NF}.Q_{NF} + C_{FF}.Q_{NF}. \quad (1)
\]

\[
V_{FF} \frac{dC_{FF}}{dt} = C_{NF}.Q_{NF} - C_{FF}.Q_{NF} - C_{FF}.Q_{FF}. \quad (2)
\]

The NF is considered to be a virtual cube with 2-m sides centered on the workers head, with volume \(V_{NF} = 8 \, m^3\), \(Q_{NF}\) is the volume airflow into and out of the FF and \(Q_{NF}\) the volume airflow into and from the NF. \(e_T\) represents the mass emission rate into the NF. \(C_{FF}\) and \(C_{NF}\) are the air concentrations in the FF and NF, respectively. Each of the terms in the equations has the dimensions of mass per unit time, e.g. \(C_{NF} [mg \, m^{-3}] \times Q_{NF} [m^3 \, s^{-1}] = [mg \, s^{-1}]\).

Note, some authors using this approach centre the NF on the source of the contaminant rather than the worker, and whilst the numerical solutions are similar to the above, we believe that if the main concern is to estimate exposure then it is more appropriate to centre the NF on the person.

Numerical solution of the simultaneous differential equations provides estimates of the concentration in the NF, which is assumed to represent the concentration inhaled by the worker. Spencer and Plisko (2007) provide the results from a study to compare this approach to measurements of solvent concentrations while washing metal parts. They identified that their measured air concentrations were generally in good agreement with the model. Similar agreement between model predictions using this approach and measurements has been shown by Nicas et al. (2006), Gaffney et al. (2008), and Nicas and Neuhaus (2008).

The model is not applicable to outdoor scenarios where there is no boundary for the FF or to indoor rooms with unidirectional forced airflow, as for example might be found in specialized rooms for spray-painting equipment. The assumption of
a compact emission source and instantaneous mixing of the contaminant throughout the NF and FF also limit the applicability and, for example, the model may not be appropriate for hot emission sources such as welding or soldering.

**Modeling continuous, intermittent, and short-term work**

In this paper, we repeated the simulations carried out by Cherrie (1999) but varied the duration of the emissions for 10 min, 30 min, 1 h, 4 h, and 8 h. Following the work of Cherrie (1999), the calculated concentration was normalized to the concentration in the NF of a 1000-m$^3$ room with 10 air changes per hour (ACH).

Numerical solutions of the simultaneous differential equations (1) and (2), above, were obtained using a fourth-order Runge-Kutta method. The starting concentrations in the NF and FF were zero and the model was run to represent a working shift (480 min), with the model time step adjusted to provide a stable solution for the equations. The emission was set at 100 mg min$^{-1}$, although once the concentrations are normalized, the magnitude of the emissions is immaterial. The FF volume was varied from 30 to 3000 m$^3$ and the number of ACH in the room varied between 0.3 and 30. Airflow from the NF to the FF was set at 10 m$^3$ min$^{-1}$, which was based on an estimate of the airflow arising from convection and some bulk air movement and was the mid-value chosen by Cherrie (1999). In this earlier work, it was concluded that within a plausible range of airflow rates from the NF, there was little variation in the magnitude of the difference between NF and FF concentrations. In our experience, the model is not sensitive to small relative differences in the size of the NF.

In addition to continuous working, we also simulated the effect of intermittent work, as might occur in a batch process—work lasting 60 min with a 60-min gap between each batch. The numerical solutions for the differential equations were obtained as described above.

**Modeling aerosol sedimentation**

To simulate aerosol dispersion, we introduced a term in the equation for losses to surfaces for aerosols and we compared these data with the results without deposition, which were taken to represent gasses and vapours.

The effect of deposition was estimated from work by Schneider et al. (1999), who estimated the deposition velocity to floor, ceilings, and walls for various particle sizes (we used their data incorporating effects of particle inertia). For particles less than ~0.3-μm diameter deposition to ceiling, walls, and floor are similarly important. However, for larger particles, the deposition velocity to the ceiling and walls become relatively less than for the floor, and for particles >2-μm diameter, losses to the ceiling are negligible. At 10 μm, the deposition velocity to the floor is ~40 times greater than the corresponding deposition velocity to the walls. For the NF, only the deposition to the floor was taken into account, and the height was set at 2 m (height of the NF space). For the FF, the losses to the floor, walls, and ceilings were included. In both cases, the deposition term in the model was expressed as an equivalent air exchange rate ($N_{eq,NF}$ and $N_{eq,FF}$), i.e. the air exchange rate that would result in the same mass loss from the model as would arise from sedimentation or other deposition mechanisms:

$$N_{eq,NF} = \frac{v_f}{2}. \quad (3)$$

$$N_{eq,FF} = \frac{(v_c + v_f)}{H} + \frac{(2 \times v_w \times (L + W))}{(L \times W)}. \quad (4)$$

where $v_f$ is the deposition velocity to the floor, $v_c$ the deposition velocity to the ceiling, and $v_w$ to the walls. $L$, $W$, and $H$ are the length, width, and height of the room.

The equivalent air exchange rates for the NF and FF were included in equations (1) and (2) as follows:

$$V_{NF} \frac{dC_{NF}}{dt} = \epsilon_T - C_{NF}.Q_{NF} + C_{FF}.Q_{NF} - \left( N_{eq,NF}.C_{NF}.V_{NF} \right). \quad (5)$$

$$V_{FF} \frac{dC_{FF}}{dt} = C_{NF}.Q_{NF} + C_{FF}.Q_{NF-CFFQFF} - \left( N_{eq,FF}.C_{FF}.V_{FF} \right). \quad (6)$$

Numerical simulations were carried out to obtain solutions for these equations as described for continuous working above for various room sizes, air exchange rates, and different monodisperse aerosols (0.3, 1, 3, 10, 30, and 100 μm aerodynamic diameter).

In order to assess the model in terms of polydisperse aerosols, typical particle size distributions were determined, from the literature, in terms of...
proportion of each particle size present in the aerosol. Particle size distributions for dusts and mists were obtained from Sabty-Daily et al. (2005), while, for fumes, a ‘typical’ particle size distribution was assumed based on data from Bonnet et al. (2000). The NF and FF parameters for each aerosol were then determined through a weighted average of the parameters obtained for each particle size, where the weighting was the proportion of particles of each size present in the substance.

**RESULTS**

Figure 1a,b show the results from the simulation for continuous emission throughout a 480-min period, for the NF and FF, respectively. Note the dashed lines in these and other figures are intended to bring out the pattern of the data and are not statistically fitted to the data. The graphs show the normalized concentration (normalized to the NF concentration in a 1000 m$^3$ room with 10 ACH) averaged over the simulation period for each room volume and ventilation condition.

Fig. 1. (a) Normalized concentration for the NF by room size and ventilation rate. Note the concentration was normalized to the NF concentration in a 1000-m$^3$ room with 10 ACH. (b) Normalized concentration for the FF by room size and ventilation rate. Note the concentration was normalized to the NF concentration in a 1000-m$^3$ room with 10 ACH.
For the NF (Fig. 1a) for large rooms (FF), the concentration was approximately unity for all ventilation conditions. As the size of the room decreased, the concentration increased, with the highest values linked to the lowest ventilation rates. For a 30-m³ room, the NF concentration with 0.3 ACH was 36 and for the 30 ACH conditions it was 1.6. The results for the FF, in Figure 1b, show that the relative difference (on the log-scale) in concentration for the various ventilation conditions was fairly constant, with the ratio of the highest to lowest concentration being ~90. For the 30-m³ room with 0.3 ACH, the average FF concentration was 35 and with 30 ACH it was 0.6. These data reproduce the original findings by Cherrie (1999).

Figure 2 shows the average normalized NF concentrations for various work durations (emission over 10 and 480 min) for a 30-m³ room for five ventilation conditions. Note the average concentration was calculated over the 8-h simulation period. For short durations, regardless of the ventilation conditions, the normalized concentrations were about unity. However, for longer emission periods, particularly for the lower ventilation conditions, the concentration was higher. Figure 3 presents the data for the ratio of the NF concentration for the 1-h to the 8-h emission period. If this ratio is equal to one, then the concentrations in both situations are identical, which was only approximately true for the 30 ACH data (ratio between 0.77 and 1—data not shown on the graph). However, for lower ventilation conditions, the difference between 1 and 8 concentrations increased, with the smallest rooms giving rise to the biggest differences. In the 0.3 ACH, simulation for the 30-m³ room was about a fifth of the concentration in the same room with continuous working. Clearly, the effect of room size and ventilation were less important for short-term tasks compared to continuous working. For rooms larger than ~300 m³ and for general ventilation rates at or above 10 ACH, the duration of the activity made little difference.

The data for intermittent working (1-h emissions followed by 1-h with no emissions) produced average normalized concentrations that were comparable to those of continuous working. The ratio of the average normalized concentration during intermittent work to that during continuous working were all around unity (data not shown), which suggests that for the purposes of modeling exposure, pollutant distribution from intermittent work can be considered equivalent to continuous work.

Figure 4 summarizes the average NF concentrations from the simulations in a 30-m³ room for different ventilation conditions for six different monodisperse particles. For very large aerosols (>30 μm aerodynamic diameter), the normalized concentration was relatively low and unaffected by the room ventilation. For smaller particles (<3 μm) the concentrations tended towards the

![Fig. 2. Normalized NF concentrations for various work durations and ventilation conditions (30-m³ room). Note the concentration was normalized to the NF concentration in a 1000-m³ room with 10 ACH.](https://academic.oup.com/annweh/article-abstract/55/9/1006/155745)
Fig. 3. Ratio of the normalized NF concentration for the 1-h simulation to the 8-h simulation. Note the concentration was normalized to the NF concentration in a 1000-m$^3$ room with 10 ACH.

Fig. 4. NF concentrations for different ventilation conditions for six different monodisperse particles (30-m$^3$ room). Note the concentration was normalized to the NF concentration in a 1000-m$^3$ room with 10 ACH.
normalized concentration obtained in the simulation without deposition, which was strongly dependant on room ventilation rate. These data suggest that for respirable aerosols, i.e. with aerodynamic diameter essentially <10 μm, the impact of aerosol deposition may be relatively small and might be reasonably ignored in a modeling framework. However, when modeling inhalable aerosol concentrations deposition may impact importantly on the modeled concentration and should be taken into account.

Use of the dispersion data in the ART

The ART is based on a mechanistic model that follows a source receptor approach within the conceptual framework of a NF and FF (Cherrie and Schneider, 1999; Tielemans et al., 2008). The model defines nine independent principal modifying factors, e.g. substance emission potential, activity emission potential, and dispersion. Within the NF and FF, the modifying factors are combined in a multiplicative manner and values for each factor are selected in the tool depending on the scenario—these are termed multipliers. The tool uses a Bayesian updating process to provide an estimate of the inhalation exposure level associated with a specific scenario. The ART is described more fully in Tielemans et al. (2011).

For the exposure multipliers for the ART model, it is clearly important to take account of the room size, the general ventilation rate, and the duration of the task; modeling of short-term exposures may be required if in REACH there is a need to make a comparison of estimated exposure with a short-term Derived No-Effect Level. For simplicity, the short-term dispersion multipliers were based on the 1-h simulations and the long-term multipliers on the 8-h simulations. Values are specified for both NF and FF sources.

Table 1 summarizes the proposed multipliers for the model by room volume and room ventilation, for continuous and intermittent work scenarios involving gasses or vapours. Note that in the model where a scenario is subdivided into a number of tasks for modeling but the scenario represents work over a whole shift then the long-term factors should be used. The duration of the whole exposure scenario should be used to select either the long-term or short-term dispersion parameters. The values in the table show the effect of the ventilation and room size on air concentration arising from a process in relation to the concentration that would be measured when the source is in the NF of the worker who is in a large room with a relatively high level of general ventilation. For example, someone doing a task over a workday with the source in their NF in a room 30 m³ with 0.3 ACH would experience a concentration 36 times higher than if they did the same thing in a large well-ventilated space (i.e. see Table 1, NF—top left cell = 36). Similarly, if the worker was not actually doing the task but was just in the large well-ventilated room, i.e. in the FF, when the task was carried out then their exposure would be one-hundredth of the exposure of the operator doing the task (Table 1, FF—bottom right cell = 0.01). Use of normalized concentrations provides a convenient way to account for the relative differences in exposure levels for different work environments and after calibration the ART can then be used to estimate exposure levels for these scenarios.

Table 2 shows the corresponding model dispersion parameters for short-term exposure scenarios for gases and vapours. These are intended to be applied where the tasks last for ~1 h or less and no other tasks involving the same substance are likely to be carried out during the same work shift. The values in these tables are generally lower than for continuous work, particularly for small rooms with poor ventilation.

For dust and mist exposures, it was assumed the aerosol size distribution was as follows: \( D < 0.3 \mu m, 4\%; 0.3–1.0 \mu m, 5\%; 1.0–3.0 \mu m, 10\%; 3.0–10 \mu m, 25\%; \) and >10 μm, 56%, based on a measured particle size distribution for paint spraying (Sabty-Daily et al., 2005). This resulted in the adjustment factors for dust and mists for long-term exposure shown in Table 3. These multipliers are also lower than the corresponding values for continuous work involving gasses or vapours (Table 1), with larger differences for small poorly ventilated rooms.

<table>
<thead>
<tr>
<th>Room volume (m³)</th>
<th>0.3 ACH</th>
<th>1 ACH</th>
<th>3 ACH</th>
<th>10 ACH</th>
<th>30 ACH</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NF multipliers</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>36.0</td>
<td>17.0</td>
<td>7.0</td>
<td>3.0</td>
<td>1.6</td>
</tr>
<tr>
<td>100</td>
<td>12.0</td>
<td>6.0</td>
<td>2.7</td>
<td>1.5</td>
<td>1.1</td>
</tr>
<tr>
<td>300</td>
<td>4.8</td>
<td>2.6</td>
<td>1.6</td>
<td>1.1</td>
<td>1.0</td>
</tr>
<tr>
<td>1000</td>
<td>2.1</td>
<td>1.5</td>
<td>1.1</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>3000</td>
<td>1.3</td>
<td>1.1</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>FF multipliers</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>35.0</td>
<td>16.0</td>
<td>6.1</td>
<td>1.9</td>
<td>0.6</td>
</tr>
<tr>
<td>100</td>
<td>12.0</td>
<td>5.0</td>
<td>1.8</td>
<td>0.6</td>
<td>0.2</td>
</tr>
<tr>
<td>300</td>
<td>3.9</td>
<td>1.6</td>
<td>0.6</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>1000</td>
<td>1.2</td>
<td>0.5</td>
<td>0.2</td>
<td>0.06</td>
<td>0.02</td>
</tr>
<tr>
<td>3000</td>
<td>0.4</td>
<td>0.2</td>
<td>0.1</td>
<td>0.02</td>
<td>0.01</td>
</tr>
</tbody>
</table>
For fume exposure, the particle size distribution: $D = <0.3\ \mu m$, 70%; 0.3–1.0\ $\mu m$, 20%; 1.0–3.0\ $\mu m$, 5%; 3.0–10\ $\mu m$, 5%; and $>10\ \mu m$, 0% was assumed, based on data for bitumen fumes (Bonnet et al., 2000). Calculation of the exposure modifiers for the fume aerosol was carried out as described above. The resulting set of multipliers for fumes for long-term exposure were quite similar to those for gases and vapours and for all practical purposes, it is possible to assume that as far as dispersion is concerned, fumes behaved similarly to gases and vapours.

### DISCUSSION

Model simulations provide an approximation to reality and one should be cautious in not over interpreting the results. However, the simple device of subdividing a room into two volumes (NF and FF) has been shown to encapsulate much of what is important in air dispersion of occupational pollutants. Cherrie (1999) noted that the model accounted for the observed differences between personal air samples, typically collected in close proximity to sources, and fixed location samples collected in the background away from the main emission sources. Other authors have used this modeling approach to compare with measured air concentrations in controlled workplace tests or real-life simulations. These studies have demonstrated that the model is a good descriptor of emissions into simple spaces. For example, Nicas and Neuhaus (2008) describe the prediction of benzene in air concentration for a solvent mixture containing between 1 and 30% benzene, used under experimental conditions. They found a strong correlation between the concentrations predicted in the NF and FF with the corresponding measured values ($r^2 = 0.94$, for both NF and FF), with the slope of the regression line being close to one. Figure 5 shows the measured benzene personal exposure levels in comparison with the predicted NF concentrations for the above study along with the data from Spencer and Plisko (2007) and Nicas et al. (2006). These show remarkably good agreement between estimated and measured values across all three studies. It therefore seems reasonable to assume that the basic model conception is appropriate for modeling exposures.

In the present work, there are several facets of the modeling that we have been unable to explore. For example, it would have been useful to explore more carefully the impact of the mixing of contaminant in the FF (in this paper, it was assumed to occur instantaneously), the size of the NF, the correlation between airflow rate in the NF and FF, and other factors. Also, the airflow between the NF and FF may change depending on the presence of a worker close to the source. However, we believe that given the overall uncertainties in the process of modeling exposure using the ART model, these aspects are unlikely to represent serious limitations. Further work to confirm this would be prudent.

Large complex shaped rooms provide some further complications to the approach described here because of the assumption about complete mixing throughout the FF are inappropriate. As a consequence, the dispersed concentration in complex shaped rooms may either be higher or lower than would be estimated from the simple analysis depending on the location of sources. We do not consider this a serious

### Table 2. NF and FF multipliers for the ART model: short-term exposure to gases and vapours

<table>
<thead>
<tr>
<th>Room volume (m³)</th>
<th>0.3 ACH</th>
<th>1 ACH</th>
<th>3 ACH</th>
<th>10 ACH</th>
<th>30 ACH</th>
</tr>
</thead>
<tbody>
<tr>
<td>NF multipliers</td>
<td>7.9</td>
<td>6.7</td>
<td>4.9</td>
<td>2.6</td>
<td>1.6</td>
</tr>
<tr>
<td>100</td>
<td>3.3</td>
<td>3.0</td>
<td>2.1</td>
<td>1.5</td>
<td>1.1</td>
</tr>
<tr>
<td>300</td>
<td>1.8</td>
<td>1.6</td>
<td>1.4</td>
<td>1.1</td>
<td>1.0</td>
</tr>
<tr>
<td>1000</td>
<td>1.2</td>
<td>1.2</td>
<td>1.1</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>3000</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>FF multipliers</td>
<td>7.0</td>
<td>5.9</td>
<td>3.9</td>
<td>1.6</td>
<td>0.6</td>
</tr>
<tr>
<td>100</td>
<td>2.5</td>
<td>2.0</td>
<td>1.3</td>
<td>0.5</td>
<td>0.2</td>
</tr>
<tr>
<td>300</td>
<td>0.9</td>
<td>0.7</td>
<td>0.4</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>1000</td>
<td>0.3</td>
<td>0.2</td>
<td>0.1</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td>3000</td>
<td>0.1</td>
<td>0.1</td>
<td>0.04</td>
<td>0.02</td>
<td>0.01</td>
</tr>
</tbody>
</table>

### Table 3. NF and FF multipliers for the ART model: long-term exposure to dusts and mists

<table>
<thead>
<tr>
<th>Room volume (m³)</th>
<th>0.3 ACH</th>
<th>1 ACH</th>
<th>3 ACH</th>
<th>10 ACH</th>
<th>30 ACH</th>
</tr>
</thead>
<tbody>
<tr>
<td>NF multipliers</td>
<td>7.9</td>
<td>6.7</td>
<td>4.9</td>
<td>2.6</td>
<td>1.6</td>
</tr>
<tr>
<td>100</td>
<td>3.3</td>
<td>3.0</td>
<td>2.1</td>
<td>1.5</td>
<td>1.1</td>
</tr>
<tr>
<td>300</td>
<td>1.8</td>
<td>1.6</td>
<td>1.4</td>
<td>1.1</td>
<td>1.0</td>
</tr>
<tr>
<td>1000</td>
<td>1.2</td>
<td>1.2</td>
<td>1.1</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>3000</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>FF multipliers</td>
<td>7.0</td>
<td>5.9</td>
<td>3.9</td>
<td>1.6</td>
<td>0.6</td>
</tr>
<tr>
<td>100</td>
<td>2.5</td>
<td>2.0</td>
<td>1.3</td>
<td>0.5</td>
<td>0.2</td>
</tr>
<tr>
<td>300</td>
<td>0.9</td>
<td>0.7</td>
<td>0.4</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>1000</td>
<td>0.3</td>
<td>0.2</td>
<td>0.1</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td>3000</td>
<td>0.1</td>
<td>0.1</td>
<td>0.04</td>
<td>0.02</td>
<td>0.01</td>
</tr>
</tbody>
</table>
limitation in most workplaces because the main determinant of risk for scenarios in REACH is likely to be the NF concentration, which is less sensitive to assumptions about dispersion in the FF.

Variations in the orientation of the worker to the source in the NF and her movement around the source may influence the actual exposure, although probably to a lesser extent than the room and general ventilation parameters. For example, Lee et al. (2007) described a set of experiments in a small room and demonstrated that workers facing a source had exposures 20% higher than when facing away from the source and 30% higher for a moving worker compared to a stationary worker (possibly because of increased turbulent mixing of the contaminant in the NF).

Differences in the behaviour of workers, both within and between individuals, are important determinants of exposure. However, even if there was considerable spatial variability in the concentration within the NF, if the behaviour of the worker in relation to the source is a random process, then the worker behaviour should not result in any bias in the predicted exposure levels, although increased variability will clearly have an important impact on the exposure distribution and hence on estimates of the upper percentile of exposure distribution. In exposure modeling, care should be taken to account for behaviour traits that may result in higher exposure and in these situations the exposure scenario should be constrained to ensure exposures remain within acceptable bounds. For example, exposure may be controlled by carefully designing a local ventilation system to minimize the effects of worker orientation to the source.

Hopkins et al. (1986a,b) investigated behavioural controls on workers exposed to styrene. They showed that worker gross behaviour, such as use of ventilation systems, other good work practices, and housekeeping measures, could be altered by training and that such changes had the potential to reduce inhalation exposure. Average reduction in exposure varied between ~50 and 85%, although it was not clear exactly which behaviour changes had the biggest effect. However, this does suggest that training may be one approach to control unacceptable exposures from behaviour traits.

Processes that involve small localized sources at elevated temperatures, e.g. a hot-melt glue gun or directed emissions from grinding or other similar sources present particular problems in relation to contaminant dispersion. In these situations, the contaminant is released within an air plume and the dispersion is therefore more localized than we have assumed in the analysis in this paper. For example, in this type of situation, it is possible for the worker to place their head in the dispersing plume giving much higher exposures than would otherwise occur. In these situations, there should be greater supervision and training for workers to help them avoid positioning themselves in the plume trajectory. We
have not attempted to model these effects but it seems probable that in some such situations there will be greater variability in worker exposure.

Coarse aerosols sediment out of the air more quickly than fumes or gases and vapours; the concentration in the NF and FF is lower when the aerosol is relatively coarse. There is limited data available to allow reliable prediction of the size distribution of an aerosol formed during a specific process. We have therefore proposed a single adjustment for typical aerosols and recommended that dispersion of fumes be treated in the same way as gases and vapours. Further work is needed to identify whether this simple approach is justified. Also, there are some vapours that have an affinity to adsorb onto surfaces giving rise to losses similar to sedimentation of particles (Montoya et al., 2009). The rate of deposition of some gases or vapours could be comparable to that for particles and further work should be undertaken to assess the importance of this in the ART model.

Overall, we conclude that it is reasonable to use the two-compartment model approach advocated by Cherrie (1999) to provide a generic way of accounting for dispersion from an indoor source in the ART. The model identifies that key factors for dispersion are the room size and general ventilation and provides quantitative modifying factors. In some specialized situations, the assumptions behind dispersion calculations may not apply and in these cases additional constraints should be placed on the use of the hazardous substances within the exposure scenario to ensure the operators are safe, e.g. specific local ventilation or training/supervision. Further research is necessary to ensure the validity of the approach to estimate dispersion in some specific circumstances.

FUNDING

Dutch Ministry of Social Affairs and Employment, Health and Safety Executive the French Agency for Environmental and Occupational Health Safety (Afsset), CEFIC LRI, Shell, GlaxoSmithKline, Eurometaux, and the British Occupational Hygiene Society (ART project).

REFERENCES


Schneider T, Kildeso J, Breum N. (1999) A two compartment model for determining the contribution of source/s surface deposition and resuspension to air and surface dust concentration levels in occupied rooms. Build Environ; 34: 583–95.


