

Conceptual Model for Assessment of Inhalation Exposure: Defining Modifying Factors

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The present paper proposes a source–receptor model to schematically describe inhalation exposure to help understand the complex processes leading to inhalation of hazardous substances. The model considers a stepwise transfer of a contaminant from the source to the receptor. The conceptual model is constructed using three components, i.e. (i) the source, (ii) various transmission compartments and (iii) the receptor, and describes the contaminant's emission and its pattern of transport. Based on this conceptual model, a list of nine mutually independent principal modifying factors (MFs) is proposed: activity emission potential, substance emission potential, localized control, separation, segregation, dilution, worker behavior, surface contamination and respiratory protection. These MFs describe the exposure process at a high level of abstraction so that the model can be generically applicable. A list of exposure determinants underlying each of these principal MFs is proposed to describe the exposure process at a more detailed level. The presented conceptual model is developed in conjunction with an activity taxonomy as described in a separate paper. The proposed conceptual model and MFs should be seen as 'building blocks' for development of higher tier exposure models.

Keywords: conceptual model; exposure determinants; inhalation exposure; modifying factors

INTRODUCTION

Exposure models are an indispensable element of exposure assessment as we will never be able to measure each exposure scenario (Jayjock *et al.*, 2007). However, establishing quantitative relationships between personal exposure levels and their determinants remains challenging, which is well reflected in the diversity of published exposure models. One approach to help understand the inhalation exposure process has been to use a source–receptor model (Smith *et al.*, 1991) and to describe exposure schematically by deterministic exposure modifiers (Schneider *et al.*, 1991; Woskie *et al.*, 1995; Creely

et al., 2005). Schneider *et al.* (1991) proposed the use of exposure factors based on 'first principles' that were mutually independent. A mechanistic model based on this approach has been developed by Cherie and colleagues (Cherie *et al.*, 1996; Cherie and Schneider, 1999).

Since the latter model is flexible and involves many steps that need expert judgment, the provision of high-quality guidance is important (Semple *et al.*, 2001). This model has been validated to some extent against workplace measurements (Cherie and Schneider, 1999; Semple *et al.*, 2001; Cherie *et al.*, 2004). Recently, the model has been used to develop a screening model called Stoffenmanager (Marquart *et al.*, 2008), which has been calibrated using a comprehensive set of measurements (Tielemans *et al.*, 2008). A similar conceptual approach was used for

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dermal exposure (Schneider *et al.*, 1999) and resulted in a transparent algorithm for dermal exposure assessment (Van Wendel de Joode *et al.*, 2003, 2005a,b).

In the present paper, we elaborate on the prior methodological work to describe inhalation exposure schematically and to impose structure on the description of the complex processes leading to inhalation exposure. It is envisaged that the source–receptor model and its visual depiction will improve the understanding of processes leading to inhalation exposure. The conceptual framework can be seen as the ‘building blocks’ for the development of a new higher tier exposure model (Advanced REACH Tool) (Tielemans *et al.*, 2007).

A SOURCE–RECEPTOR MODEL

The conceptual model is based on a stepwise transport of a contaminant from the source to the receptor (Smith *et al.*, 1991; Creely *et al.*, 2005). It is constructed using three types of components, i.e. sources, compartments through which the contaminants may pass from the source to the receptor, and the receptor. The model includes four mechanisms for transport of a contaminant: (i) separation of gas or vapor molecules or solid particles from the parent material (source strength) (ii) transport of the contaminant to and between compartments, (iii) loss of

contaminants from compartments due to sinks (e.g. local ventilation, cleaning) and (iv) uptake by the receptor (Fig. 1). This paper first describes the components and transport mechanisms and then proposes an approach to their quantification by using modifying factors (MFs).

Model components

Source. The source component represents an activity during which a hazardous substance is emitted into the air. The source can be either stationary or mobile and the strength of the source is dependent on characteristics of the activity and features of the product itself (Plinke *et al.*, 1991). The constrained transport of energy to the parent product related to an activity causes a substance to be released from the parent product and to become airborne. Once molecules or particles have been separated from the parent material, induced air movements will transport the liberated material away from the source. In theory, a source may also be diffuse and difficult to localize, e.g. emission due to leaking machinery. Spills or other contaminants on surfaces are included in the surface compartment.

Compartments. *Local control influence region:* A virtual boundary around a source is proposed. This boundary delimits the ‘local control influence region’ (LCIR) and represents the zone of influence for

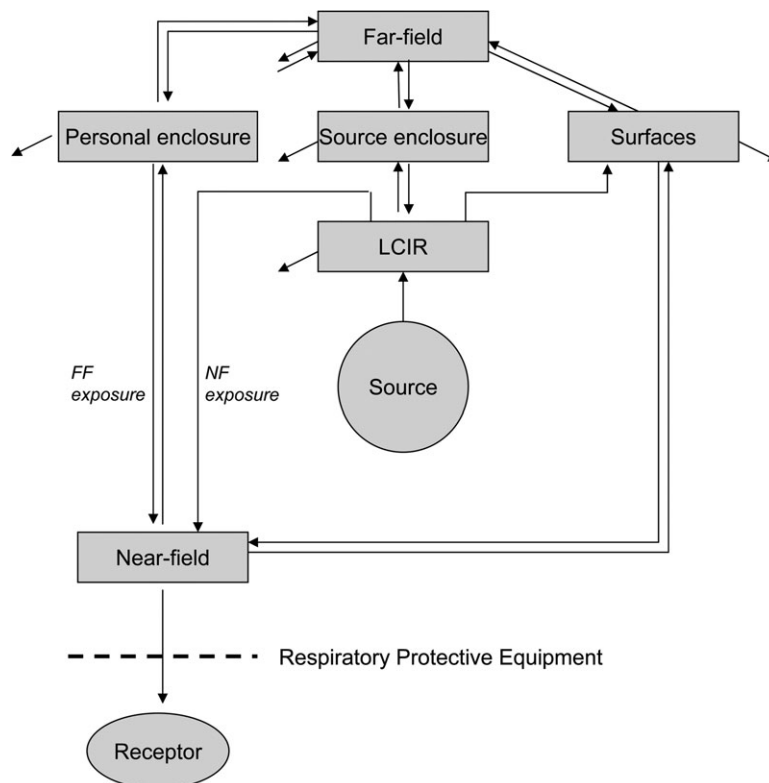


Fig. 1. Conceptual model for inhalation exposure including sources, compartments and receptor and transport between these components.

a given local control system. The LCIR boundary may be determined by a physical barrier to contain the substance (e.g. screens or airborne capture sprays) and the range of influence of the local exhaust ventilation (that would be determined by capture velocity, type of hood, etc.). The local exhaust ventilation is also a sink that removes contaminant from the LCIR. More than one local control and thus LCIR may be related to a particular source.

Near-field and far field: The near-field (NF) compartment is conceptualized as a volume of air within 1 m in any direction of the worker's head. The far field (FF) comprises the remainder of the room. Hence, the concept of NF–FF can be considered as a box-inside-of-a-box, where the worker moves around in the FF zone with an enveloping NF zone. In the proposed conceptual model, a source is referred to as an NF source or an FF source depending on its location relative to the worker. The boundaries of the NF are somewhat arbitrary chosen and follow previous work by Cherrie and Schneider (1999). Others have proposed a two-zone approach, where the NF zone is centered around the source instead of the worker (Nicas, 1996; Spencer and Plisko, 2007). However, we prefer to define the NF around the worker as this places the focus on the worker and hence personal exposure.

The concentration decreases with increasing distance from the source due to mixing with background air. In many cases, the mixing is caused by a non-directional, random airflow resulting in uniform dispersion. The airflow in workrooms arises mainly from turbulent motion of the air and so-called eddies due to obstacles in the path of moving air, localized convection currents induced by temperature differences and movement of machines and workers (Roach, 1981). The present approach lumps concentration gradients into the two compartments NF and FF. This approach assumes perfect mixing in the two compartments with transport between the two compartments due to local airflows and turbulence. The airflows are dependent on features like room shape and size, general ventilation, movement of other workers or equipment (e.g. fork-lift trucks), convection from heat sources in the room and the physical work rate of the worker. The processes determining these airflows are poorly understood (Feighley *et al.*, 2002). However, theoretical work of Cherrie (1999) showed that some general assumptions can be made about the effects of room size and general ventilation characteristics on the relationship between concentrations in the NF and FF zones.

The assumption of perfect mixing may lead to substantial error in exposure assessment where workers are positioned very close to the source. Moreover, the perfect mixing assumption does not consider local disturbances in the flow field very close to the worker. Examples of factors that may have impact

on contaminant levels in the breathing zone are convection as a result of body temperature, formation of wakes or arm movements (Flynn and George, 1991; Flynn and Ljungqvist, 1995; Welling *et al.*, 2000). These phenomena may be simulated using specific computational fluid dynamics (Bennett *et al.*, 2000), but cannot be explicitly dealt with in generic models. In the present approach, this problem is dealt with by introducing a MF, to be described later.

The conceptual model is specifically focusing on indoor worker environments. Modifications will be needed for describing the dispersion pattern in outdoor situations.

Source enclosure and personal enclosure: Additional compartments defined by enclosures can be added if relevant. A source, for example, may be placed in a compartment that isolates the source from the work environment. This compartment is referred to as the source enclosure. Likewise, a worker may be inside an air-conditioned cabin; this compartment is referred to as a personal enclosure.

Surfaces: Surfaces (e.g. workbench, wall, but also personal clothing) that have been contaminated by the chemical of interest through general deposition in the work environment or adsorption constitute the surface compartment or several distinct compartments if needed. The deposition may result in permanent loss of contaminant, e.g. due to cleaning activities. Alternatively, surface contaminants may be transported to the NF or FF compartment through resuspension or evaporation, e.g. due to moving equipment, worker movement and draughts. The transport rate of contaminants from the surface compartment is difficult to predict and depends on, among others, factors such as cleaning procedures and level of 'good house keeping' (Buringh *et al.*, 1992; Lumens *et al.*, 1993). It is important to note that treated or contaminated surfaces that constitute a clearly defined source of emission (e.g. handling of treated objects, treated surfaces during brushing, drying rack) are addressed as a source component.

Receptor: This component represents the respiratory tract of the worker. Respiratory protective equipment (RPE) forms a barrier for air contaminants that reduces uptake by the receptor.

Transport mechanisms

Figure 1 also shows the transport of contaminant between model compartments representing the exposure pathways from the source to the worker (indicated by the arrows between compartments). Some arrows leave the compartments without leading to other compartments, signifying losses from the system. For example, the arrow leaving the LCIR compartment indicates the loss of contaminant mass removed by a local control measure.

The rate at which a contaminant is emitted from the source is the gross source output rate, expressed as mass

per unit time. A fraction of the emitted contaminant escapes the LCIR compartment and the corresponding transport rate is the net source output rate.

Turbulence and large eddies subsequently transport the airborne contaminant directly to the NF or to the FF depending on the location of the source. Where a source or a personal enclosure exists, the source is by definition in the FF. In case of a source enclosure, part of the contaminant is removed and the remaining fraction is transported to the FF. In a similar fashion, the personal enclosure (e.g. when the worker carries out an activity within a cabin) reduces contaminant transport to the NF. Contaminants may also be transported to surrounding surfaces; a fraction may leave the system due to cleaning or other loss processes and by evaporation or resuspension a fraction may again be transported to the NF or FF.

The model depicts one source component, although in reality multiple sources are often present in a workplace. All these sources will release contaminants and transport of these contaminants will follow the processes as indicated in Fig. 1.

QUANTITATIVE EXPOSURE ESTIMATION ALGORITHM

Modifying factors

Nine principal MFs are proposed that are associated with the model components: two for the source

component and one for each of the other model components (Table 1). The MFs are defined at a high level of abstraction in order to be applicable across a broad range of scenarios. The MFs are defined so that they are virtually mutually independent from a physico-chemical point of view. In order to be useful for exposure modeling, these MFs have to be uniquely identifiable, observable, quantifiable and be applicable across a wide range of different exposure scenarios. Each MF has a number of underlying determinants that are defined at a low level of abstraction and thus much more specific; examples of these underlying factors are discussed later.

The emission rate at the source is a function of the type of activity and characteristics of the substances used. The MF 'activity emission potential' describes the potential of the activity to transport contaminants into the LCIR compartment and is determined by characteristics such as type (e.g. motive forces, heat) and amount of energy transfer, scale (e.g. amount product used) and product-to-air interface (interaction between product and adjacent air).

The 'substance emission potential' describes the potential of the product to become airborne. For particulate agents, the potential to become airborne is dependent on dustiness. For liquids and liquid mixtures, the potential to become airborne is dependent on volatility.

The LCIR is related to the principal MF 'localized control', representing the efficiency of control measures in close proximity of the source. The impact of

Table 1. Components of the conceptual model and related principal MFs

| Model component | Principal MF | Description |
|--------------------|--|---|
| Source | Activity emission potential (H) ^a | Describes the potential of the activity to generate exposure and is determined by the following characteristics: type and amount of energy transfer, scale (e.g. amount product used) and product-to-air interface (e.g. level of containment). |
| | Substance emission potential (E) | Determines the intrinsic emission potential of a substance, i.e. dustiness for particulate agents and volatility for liquids. |
| LCIR | Localized control (LC) | Control measures in close proximity of the source intended to remove emissions, e.g. local exhaust ventilation, airborne capture sprays. |
| Source enclosure | Segregation (Seg) | Isolation of sources from the work environment without containment of the source itself, e.g. separate drying room. |
| NF and FF zone | Dilution (D) | Natural and mechanical ventilation characteristics, determining the dilution of air contaminants through the room, i.e. between NF-FF zone and FF outside. |
| NF zone | Personal behavior (P) | Orientation and distance of the worker to the source in the NF, determining the potential exposure, e.g. worker positioned at very close distance during precision work, overhead work. |
| Personal enclosure | Separation (Sep) | Providing a worker with a personal enclosure within a work environment, e.g. air conditioned cabin. |
| Surfaces | Surface contamination (Su) | Emission related to release of deposited contaminants on surrounding surfaces (including worker clothing) due to natural means or general workplace activities (e.g. moving equipment/vehicles). |
| Receptor | RPE | Efficiency of RPE preventing the inhalation of airborne substances (not addressed in this paper). |

^aThis principal MF is described in detail in an accompanying paper (H. Marquart, T. Schneider, H. Goede, M. Tischer, J. Schinkel, N. Warren, W. Fransman, M. van Tongeren, H. Kromhout, E. Tielemans, J. Cherrie, 2008, in preparation).

a source enclosure is accounted for by 'segregation', describing the effectiveness of isolation of sources from the work environment. A 'dilution' factor describes the influence of mechanical and natural ventilation and room size on the concentration in the NF or FF compartments. The principal MF 'worker behavior' is defined to take account of the influence due to worker movement, worker posture, possible worker posture very close to the source and other factors causing deviations from a completely mixed NF. The principal MF 'separation' describes how effective the concentration in the personal enclosure compartments is reduced relative to the FF in which it is embedded. Note that a personal barrier, if present, encapsulates the person and could thus be taken as the NF zone. Transport into NF or FF due to release of deposited contaminants on surfaces is described by the principal MF 'surface contamination'. The MF 'respiratory protective equipment' is not addressed in this paper.

Structure of algorithm

Esmen (1979) used MFs in a multiplicative manner for retrospective exposure assessment. However, as previously proposed by Cherrie and Schneider (1999), we treat the various exposure sources in the NF and FF zones as additive terms, while MFs describing release and dispersion of a particular source are incorporated in a multiplicative manner. The algorithm from Cherrie and Schneider (1999) is extended using the list of nine principal MFs in the equations below.

The total personal exposure level (C_t) is the sum of exposure levels due to NF (C_{nf}) and FF (C_{ff}) contributions, adjusted for possible use of RPE:

$$C_t = (C_{nf} + C_{ff}) \cdot RPE. \quad (1)$$

Personal exposure due to sources in the NF (C_{nf}) is a multiplicative function of substance emission potential (E), activity emission potential (H), localized control (LC), personal behavior (P) and dilution (D). In addition, exposure may arise due to transport of substance from surfaces in the NF [surface contamination (Su)]:

$$C_{nf} = (E_{nf} \cdot H_{nf} \cdot LC_{nf} \cdot P_{nf} + Su_{nf}) \cdot D_{nf}. \quad (2)$$

Personal exposure due to sources in the FF (C_{ff}) is a multiplicative function of substance emission potential (E), activity emission potential (H), localized control (LC), segregation (Seg), dilution (D) and separation (Sep). In addition, exposure may arise due to transport of substance from surfaces in the FF [surface contamination (Su)]:

$$C_{ff} = (E_{ff} \cdot H_{ff} \cdot LC_{ff} \cdot Seg_{ff} + Su_{ff}) \cdot D_{ff} \cdot Sep_{ff}. \quad (3)$$

Note that there are differences between equations describing exposure related to NF and FF sources.

Segregation and separation are not relevant for NF sources, whereas the personal behavior is not relevant for FF sources. The factor dilution will be different for FF sources as compared to NF sources. Cherrie (1999) has suggested numerical values for this factor for NF and FF sources on a relative scale. The equations apply for a situation where operational conditions remain stable.

In complex work environments, multiple sources of various source strengths may be present in both the NF and FF. In theory, the contribution of each source should be calculated separately and then added for the NF and FF. In practice, however, it may not be feasible to take into account all sources. A pragmatic solution may be to take into account only the main sources in the NF and FF. In case that a person is conducting different consecutive tasks during a time period, each task should be assessed separately and a time-weighted average should be calculated.

Quantification

In order to use the equation to predict a concentration unit (e.g. mg m^{-3}), different approaches can be followed. From a mechanistic point of view and following from the conceptual framework, the substance emission potential can be assigned the unit of an emission rate (mass per time unit), whereas the dilution has the unit of a reciprocal of a ventilation rate (time unit per volume). The other principal MFs are dimensionless.

Alternatively, Cherrie and Schneider (1999) followed a more pragmatic approach that proved to be feasible in various work situations. They assigned unit of concentration to the substance emission potential, whereas the other terms were defined as dimensionless quantities. Hence, this approach represents the concentration generated during a standardized task and operational conditions. This approach of assigning a 'target value' has shown to be successful in the quantitative assessment of different exposures across 40 tasks (Semple *et al.*, 2001).

Finally, all MFs may be defined as dimensionless quantities operating on a given baseline estimate. The latter approach has been used to estimate historical exposure by multiplying contemporary exposure measurement results by dimensionless exposure modifiers (Armstrong *et al.*, 1996; Lewis *et al.*, 1997). The dimensionless algorithm may also be fitted to available exposure measurements using regression techniques to arrive at an equation predicting a concentration unit. Recently, a screening level model called Stoffenmanager has been calibrated in this manner (Tielemans *et al.*, 2008). Mixed-effects models were used to enable the mechanistic model to predict actual exposure rather than just relative exposures.

UNDERLYING DETERMINANTS OF EXPOSURE

A broad range of exposure determinants has already been documented in exposure assessment studies (Burstyn and Teschke, 1999). Important determinants that are observable at the workplace are briefly discussed here; Table 2 describes underlying determinants related to the source component, whereas the underlying determinants of the remainder of the principal MFs relevant for transport between and loss from compartments are described in Table 3. Both tables provide some important examples of underlying determinants but should not be considered to be comprehensive. We are currently assigning values to the principal MF and in the context of this subsequent work we will describe the underlying determinants and related literature in more detail in the future.

Determinants related to the source

The principal MF activity emission potential can be characterized in relation to three categories of determinants. First, emission is dependent on the level and type of transfer of energy. The type of energy transfer can be very diverse and to adequately describe this MF, the type of energy transfer is divided into five classes:

1. Motive forces—emissions primarily related to movement of product or movement of objects contaminated with a product. It excludes motion where friction is caused between bound materials.
2. Gravitational and impaction forces—emissions primarily related to forces during falling and caused by the final impact on surfaces.

3. Friction—emissions primarily caused during an activity where friction between bound materials and collisions induced by friction causes comminution. The target product may include (lubricating) liquids added to these activities.
4. Pressure drop and other dispersion forces—emissions primarily caused by pressurized sources or other forces/techniques causing intentional or unintentional dispersion into the air.
5. Heat—the emission (generally of vapors) is largely from the temperature of a product that, together with the temperature of the surrounding of the product, leads to emission of vapors. Heat energy may be actively applied, e.g. when a liquid is heated, it may be the result of a chemical reaction process, but it may also be passively present, e.g. when there is evaporation from a liquid at room temperature.

Second, the scale of the activity is relevant in terms of emission potential. The influence of scale will depend on the type of activity and material. For instance, scale can be expressed in terms of processing rate of a product, i.e. amount of product produced or number of pieces processed per time unit (e.g. for weighing a product). Alternatively, surface contamination or surface area may be a more relevant underlying determinant of scale in other activities (e.g. for working with a vapor degreasing bath). It should be noted that level of energy transfer and scale during an activity may be influenced by personal behavior and skills of the individual worker. One may for instance envisage that less skilled workers may handle substances in a more uncontrolled manner resulting in more energy transfer.

Table 2. Principal MFs related to source strength and examples of underlying determinants

| Principal MF | Underlying determinants |
|------------------------------|---|
| Activity emission potential | Type and amount of energy transfer: <ul style="list-style-type: none"> • Motive forces (non-frictional). Amount is determined by e.g. level of agitation, velocity, reactivity • Gravitational and impaction forces. Amount is determined by e.g. dropping height, hardness of receiving surface • Frictional forces. Amount is determined by e.g. velocity, capacity, friction coefficient • Pressure drop and other dispersion forces. Amount is determined by e.g. pressure, level of dispersion force • Heat. Amount is determined by e.g. processing temperature (melted solids), voltage, agitation Scale: <ul style="list-style-type: none"> • Application rate (kg or l hr^{-1}), amount produced or processed per time ($\text{m}^3 \text{hr}^{-1}$) • Level of surface loading, surface area handled Product-to-air interface: <ul style="list-style-type: none"> • Confinement technologies (e.g. closed system, closed but breaching system, lids on vessels, hatches) • Specialized technologies (e.g. bottom loading) |
| Substance emission potential | Dustiness: <ul style="list-style-type: none"> • Particle size (distribution) • Aggregation/coalescence/cohesion/friability • Moistness of product (if not related to airborne capture sprays) • Solidity/intactness/corrosion/surface modification of bound materials Volatility: <ul style="list-style-type: none"> • Partial vapor pressure, diffusion coefficient in air |

Table 3. Principal MFs related to dispersion and examples of underlying determinants

| Principal MF | Underlying determinants |
|-----------------------|--|
| Local control | LEV: <ul style="list-style-type: none"> • Type of exhaust system (e.g. LEV type, capture velocity, distance between source and hood) • LEV enhancements (e.g. encapsulation, air supply at/behind worker) • Critical conditions of use (good/poor practice) • Maintenance of system Suppression techniques: <ul style="list-style-type: none"> • Type of airborne capture sprays • Thoroughness of wetting (e.g. velocity and quantity water used, angle nozzles) • Enhancement techniques (e.g. finely atomized, electrostatic charging, foams, surfactants, fog) Chemical stabilization: <ul style="list-style-type: none"> • Type of chemical technique (e.g. volatility of suppressants) • Critical conditions (e.g. amounts used) Physical stabilization: <ul style="list-style-type: none"> • Type of physical technique (e.g. oil, saw dust) • Critical conditions (e.g. amounts used) |
| Segregation | <ul style="list-style-type: none"> • Type of segregation [e.g. curtains, screens, separate (enclosed) room, covering with foil, tarpaulins] • Degree of segregation (e.g. partial/complete, separate room with/without extraction ventilation) |
| Dilution | Indoors: <ul style="list-style-type: none"> • Ventilation type and design, e.g. natural, mechanical, special ventilation (booths, walk-in cabinets) • Ventilation airflow rate and room size (nominal air exchange rate) • Conditions (e.g. plume away/towards worker, mobile activities, obstacles between source worker) • Operation/maintenance of ventilation system Outdoors: <ul style="list-style-type: none"> • Meteorological conditions (e.g. wind speed, wind direction, atmospheric stability) |
| Separation | <ul style="list-style-type: none"> • Type of separation (e.g. closed room or cabin, open booth or cabin) • Degree of separation (e.g. partial/complete, cabin with/without fresh air supply) |
| Personal behavior | <ul style="list-style-type: none"> • Worker-source orientation (e.g. overhead work, worker posture to source, orientation of application) • Worker-source distance (e.g. manual/automated, close-up precision work, length tool handle) |
| Surface contamination | <ul style="list-style-type: none"> • Location of surface (e.g. clothing, nearby work surfaces) • Contamination level (e.g. wet/dusty clothing and surfaces) • Disturbances (draughts, convection, vibration, vehicles) |
| RPE | <ul style="list-style-type: none"> • Type of RPE • Critical condition of use (e.g. fit of device) • Maintenance |

LEV, local exhaust ventilation.

Third, product-to-air interface describes an activity in terms of the extent to which the substance interacts with the adjacent air. Again, the product-to air interface can be described in different ways. For activities where the product is intentionally transferred through the air or displaced across surfaces, the interaction may be influenced by e.g. surface area, surface characteristics (e.g. influencing retention), application techniques and transfer characteristics (e.g. transfer efficiency). Product-to-air interface may be closely related to scale of the activity and as such cannot be considered completely independent.

For different activities, various combinations of the above determinants may be applicable, implying that different combinations of underlying exposure determinants are relevant across the whole spectrum of occupational activities. Hence, identification of the underlying determinants of the activity emission potential is difficult in a generic sense. Therefore, a clustering scheme is proposed in a separate paper (H. Marquart, T. Schneider, H. Goede, M. Tischer, J. Schinkel, N. Warren, W. Fransman, M. van Tongeren, H. Kromhout, E. Tielmans, J. Cherrie, 2008, in preparation) that provides a method of structuring activities in generic groups characterized by processes that are similar

regarding type of energy transfer, scale and product-to-air interface. Such a clustering scheme was used earlier for modeling dermal exposure (Van Hemmen *et al.*, 2003). This helps to subsequently assign scores for this principal MF, separate for different generic groups.

The principal MF substance emission potential is determined by dustiness for particulates and volatility for liquids. Table 2 describes the distinct underlying determinants that are important with respect to dustiness and volatility. Volatility is strongly related to vapor pressure of a substance which itself is strongly related to temperature of the liquid. Substances with very high vapor pressure should be considered separately as they are already in the gas state and are by definition airborne. Likewise, at the other end of the spectrum, substances with very low vapor pressure do not evaporate and exposure occurs due to formation of aerosols as a result of handling the product. For a substance in a mixture, one should ideally use the mole fraction of the substance to predict partial vapor pressure. However, there is generally only limited information available on characteristics of a mixture. In addition, prediction of volatility for mixtures can be difficult for non-ideal mixtures (Olsen *et al.*, 1992; Nielsen and Olsen, 1995; Fehrenbacher and

Hummel, 1996). Mixtures of solids and liquids have a further complexity because the emissions are not constant with time because as the mixture dries a solid film may form over the surface.

Dustiness can be defined as the propensity of a material to generate airborne dust during its handling. Dustiness is not a fixed physical or chemical property of a substance and depends on particle size, humidity and the nature of the adhesive forces (Lidén, 2006). This can be evaluated using standardized dustiness tests. Some explorative attempts have been made to study dustiness test results in relation to exposure for powdered and granular material (e.g. Brouwer *et al.*, 2006). Dustiness characteristics have also been studied in relation to fiber exposure (e.g. Schneider, 1995). Several screening tools, such as COSHH Essentials and Stoffenmanager, incorporate dustiness in relative categories. Yet, at present, the relevance of qualitative terminology like 'coarse dust' and 'fine dust' in terms of dustiness is poorly understood and should be explored further.

Determinants related to compartments

The transport between compartments is described by the other seven principal MFs and related underlying determinants (Table 3). For localized control, a distinction can be made between underlying determinants related to local ventilation, suppression techniques, chemical stabilization and physical stabilization. The efficacy of control measures is determined by technology aspects (e.g. capture velocity), critical conditions of use and maintenance of systems (Popendorf, 2006).

The effectiveness of segregation is determined by type and degree of segregation of the source. This also applies for separation. A worker may reside in a cabin or room that is completely or partially enclosed. In addition, the room may be ventilated or not.

Dilution in the NF and FF zones has different underlying determinants for indoor and outdoor work. For indoor work, ventilation type, airflow rates and room size are dominant factors (Cherrie, 1999). Dilution in outdoor situations is heavily influenced by meteorological conditions and only very limited experience exists to model this for occupational exposures.

The principal MF personal behavior includes the influence of working methods and is determined by both the orientation and distance between worker and source. Some activities may be very prone to behavior (e.g. manual handling of substances), whereas other activities are not prone to behaviour (e.g. remote working, working isolated from process). This principal MF can cover worker skills and habits as it has been shown by Vermeulen *et al.* (2000) that seniority was related to exposure, suggesting that professional skills can have impact.

The relevance of surface contamination is determined by level of surface contamination and the po-

tential for disturbances at the workplace. It is very difficult to propose objective measures for this MF, but the extent of contamination may be related to type of industry (e.g., pharmaceutical industry vs. foundries), cost of substance (less contamination when using expensive substances), and toxicity (less contamination when using obviously toxic substances). Location of the surface is very important as for instance contaminations on clothing may result in substantial exposure gradients in the NF, whereas other surfaces probably result in relatively homogeneous dispersion in the NF.

DISCUSSION

Databases with repeated inhalation (Kromhout *et al.*, 1993; Rappaport *et al.*, 1993; Symanski *et al.*, 2006) and dermal (Kromhout and Vermeulen, 2001; Kromhout *et al.*, 2004) exposure measurements from a variety of workplaces and industries provide evidence of substantial variation between workers and even more of temporal variation. Some fundamental work describing the processes leading to this exposure variation has already been completed. Both empirical modeling of exposure data (e.g. Rappaport *et al.*, 1999; Burstyn *et al.* 2000) and mechanistic modeling (e.g. Cherrie and Schneider, 1999; Keil, 2000; Nicas and Armstrong, 2003) have provided insight into sources of spatial and temporal exposure variation. The goal of this paper was to further evaluate the processes leading to inhalation exposure and to integrate these processes in a conceptual model.

Considering each step in the process of inhalation exposure from the source to the worker helps to explicitly define the assumptions with respect to exposure and provides a foundation for model development. The proposed conceptual model in conjunction with the principal MF and underlying determinants should be seen as building blocks for development of a new mechanistic exposure model that is currently under development (Tielemans *et al.*, 2007). This paper can be considered a first step in this development.

The MFs as proposed in the present paper are subdivided into nine relevant and distinct classes. The optimal resolution or number of classes for each MF and the assigned values should be based on the state of the art evidence and views in the exposure assessment community. An expert elicitation procedure (Morgan and Henrion, 1990) is needed combining available empirical evidence and expert judgment to arrive at such a view. This approach will be feasible for various MF such as localized controls, segregation, separation, mixing and surface contamination. Additional methodological work on indoor and outdoor transport processes is required to adequately describe exposure in various working environments.

An activity taxonomy and clustering scheme for activities needed to transparently assess exposure potential of activities has been developed by H. Marquart, T. Schneider, H. Goede, M. Tischer, J. Schinkel, N. Warren, W. Fransman, M. van Tongeren, H. Kromhout, E. Tielemans, J. Cherrie (2008, in preparation).

The methodological work may also contribute to further development of other, existing exposure models such as Stoffenmanager (Tielemans *et al.*, 2008), COSHH Essentials (Russel *et al.*, 1998) and the ECETOC TRA (ECETOC, 2004). The opposite is also true; the absence of a formal underlying conceptual model was the basis of critique in the evaluation of EASE (Creely *et al.*, 2005). Ideally, different screening and more advanced models for exposure assessment should all have a common underlying conceptual model, although models may differ in terms of resolution, (worst-case) assumptions, etc.

In addition, the proposed list of MFs could be adopted as the basis for a standardized approach for recording core contextual information in conjunction with already existing guidelines (Rajan *et al.*, 1997; Tielemans *et al.*, 2002). Systematic collection of data on the MFs in new exposure studies and subsequent statistical analyses of the data ensure a growing evidence base. This may improve the ability of the model to predict exposure adequately. We are currently collating exposure data with sufficient contextual information from various institutes and industries in order to quantify the proposed mechanistic model. In the context of the Advanced REACH Tool project, part of the collated exposure measurements will be used for cross-validation of the model in a later phase.

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