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Advanced Reach Tool (ART): Development of the Mechanistic Model

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This paper describes the development of the mechanistic model within a collaborative project, referred to as the Advanced REACH Tool (ART) project, to develop a tool to model inhalation exposure for workers sharing similar operational conditions across different industries and locations in Europe. The ART mechanistic model is based on a conceptual framework that adopts a source receptor approach, which describes the transport of a contaminant from the source to the receptor and defines seven independent principal modifying factors: substance emission potential, activity emission potential, localized controls, segregation, personal enclosure, surface contamination, and dispersion. ART currently differentiates between three different exposure types: vapours, mists, and dust (fumes, fibres, and gases are presently excluded). Various sources were used to assign numerical values to the multipliers to each modifying factor. The evidence used to underpin this assessment procedure was based on chemical and physical laws. In addition, empirical data obtained from literature were used. Where this was not possible, expert elicitation was applied for the assessment procedure. Multipliers for all modifying factors were peer reviewed by leading experts from industry, research institutes, and public authorities across the globe. In addition, several workshops with experts were organized to discuss the proposed exposure multipliers. The mechanistic model is a central part of the ART tool and with advancing knowledge on exposure, determinants will require updates and refinements on a continuous basis, such as the effect of worker behaviour on personal exposure, 'best practice' values that describe the maximum achievable effectiveness of control measures, the intrinsic emission potential of various solid objects (e.g. metal, glass, plastics, etc.), and extending the applicability domain to certain types of exposures (e.g. gas, fume, and fibre exposure).

Keywords: determinants of exposure; expert judgement; exposure assessment; exposure modeling; occupational exposure; mechanistic model

INTRODUCTION

REACH (Registration, Evaluation and Authorization of CHemicals), the new chemicals policy in Europe, requires exposure estimates for a large variety of

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chemical agents and scenarios. In the absence of sufficient exposure measurement data, a tiered approach has been advocated, in which the Tier 1 approach calls for a conservative exposure assessment using screening tools (ECHA, 2008). Several screening tools for inhalation exposure have been developed, including the ECETOC TRA (ECETOC, 2004), the Stoffenmanager (Marquart *et al.*, 2008), and the EMKG-Expo-Tool (http://www.reachhelpdesk.de/en/exposure/exposure.html). However, a more refined exposure assessment tool such as the Advanced REACH Tool (ART) is also needed to provide more realistic exposure estimates in a Tier 2 assessment.

The ART project comprises of several components (Tielemans *et al.*, 2011). The development of the mechanistic model is described in this paper, with emphasis on the characterization of the principal modifying factors (MFs), its underlying determinants, and assignment of multipliers for each determinant. The approach is illustrated with a worked example. A detailed report of the mechanistic model can be found on the website www.advancedreachtool.com.

STRUCTURE OF THE MECHANISTIC MODEL

The mechanistic model is based on a conceptual framework that adopts a source receptor approach (Cherrie and Schneider 1999; Tielemans *et al.*, 2008). The framework describes the 'transport' of a contaminant from the source to the receptor and defines nine independent principal MFs. The workspace is divided into two compartments: the near-field centred on the worker (within 1 m from the worker's head) and the far-field comprising the remainder of the workspace.

Figure 1 shows a flow diagram of the ART mechanistic model, indicating the various MF along the source-receptor pathway. ART currently differentiates between three different exposure types: vapours, mists, and dust (fumes, fibres, and gases are presently excluded). Furthermore, a structured approach was developed, based on a range of specific activity classes (Marquart *et al.*, 2011) to determine the impact of the workplace activity on emission (i.e. 'activity emission potential'). Thus, the model is activity specific and developed in such a way that a distinction is made between different types of exposures (dust, mist, and vapour).

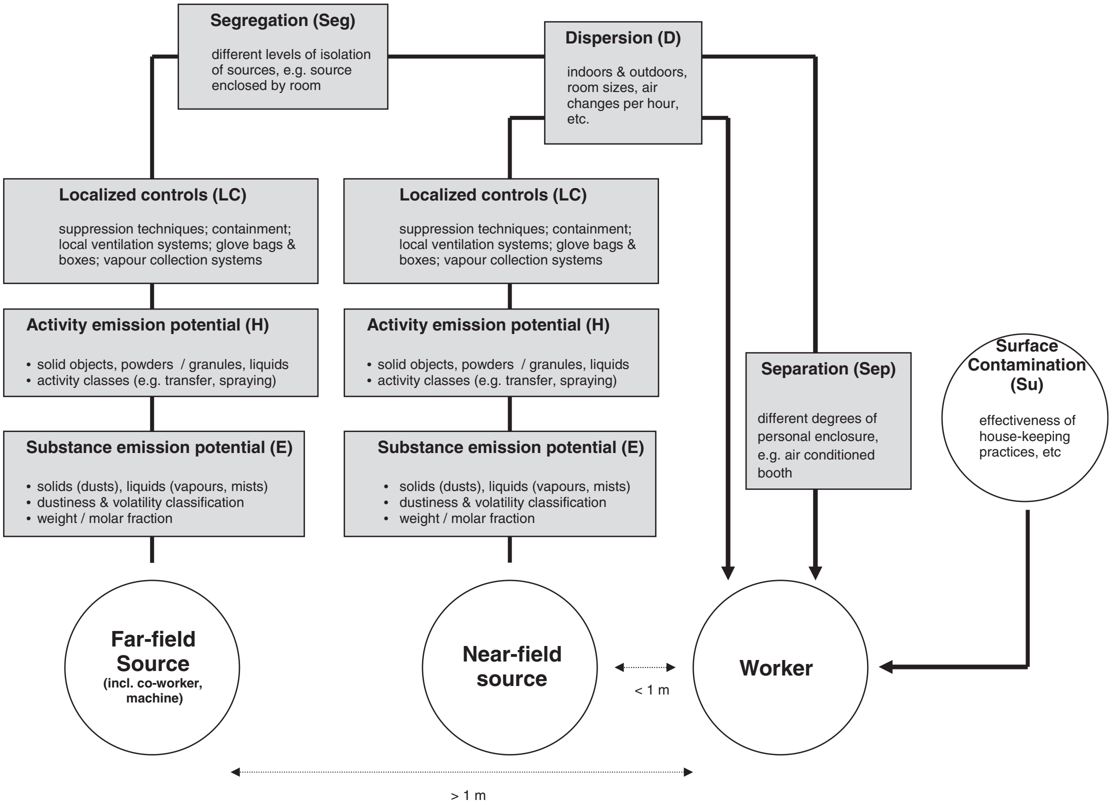

Fig. 1. Flow diagram of the ART mechanistic model.

Depending on the exposure scenario, some MFs are not relevant to estimate exposure (Table 1). For example, segregation (Seg) and personal enclosure/separation (Sep) only apply to far-field sources because in both cases, it is assumed that the distance between the source and breathing zone of the worker exceeds 1 m. Because ART estimates the concentration in the breathing zone of a worker, respiratory protective equipment (RPE) is currently not considered and therefore excluded in Fig. 1. Also, we were not able to objectively quantify the effect of the MF 'worker behaviour' on personal exposure levels (Meijman *et al.*, 1996) and because ART is meant to assess exposure across different plants and sites, we felt that 'worker behaviour' is part of the variability between workers in a company. Therefore, the effect of this MF is reflected in the percentile of the exposure distribution and not in the mechanistic model. This is described in more detail by Erik Tielemans *et al.* (2011).

The model consists of one algorithm to estimate the contribution from near-field (NF) [equation (1)] and one for estimating the contribution from far-field (FF) sources [equation (2)]. Personal exposure from a near-field source (C_{nf}) is a multiplicative function of substance emission potential (E), activity emission potential (H), (primary) localized control (LC_1), secondary localized control (LC_2; in case two localized controls are used simultaneously, e.g. wet suppression and local exhaust ventilation), and dispersion (D). The algorithm for a far-field source (C_{ff}) also includes segregation (Seg) and personal enclosure/separation (Sep).

$$C_{\mathrm{nf}} = \left(E_{\mathrm{nf}} \cdot H_{\mathrm{nf}} \cdot \mathrm{LC}_{\mathrm{nf1}} \cdot \mathrm{LC}_{\mathrm{nf2}}\right) \cdot D_{\mathrm{nf}}, \qquad (1)$$

$$C_{\mathrm{ff}} = \left(E_{\mathrm{ff}} \cdot H_{\mathrm{ff}} \cdot \mathrm{LC}_{\mathrm{ff1}} \cdot \mathrm{LC}_{\mathrm{ff2}} \cdot \mathrm{Seg}_{\mathrm{ff}}\right) \cdot D_{\mathrm{ff}} \cdot \mathrm{Sep}. \qquad (2)$$

The level of surface contamination (Su) for each activity depends on the location of the source, i.e. whether there is (i) a near-field source only [equation (3)], (ii) a far-field source only [equation (4)], or (iii) both near- and far-field sources [in which case the surface contamination in the near-field is assumed to dominate that of the far-field, see equation (3)]:

$$\mathrm{Su}_{\mathrm{nf}} = \mathrm{Su}_{\mathrm{factor}} \cdot \left(E_{\mathrm{nf}} \cdot H_{\mathrm{nf}} \cdot \mathrm{LC}_{\mathrm{nf1}} \cdot \mathrm{LC}_{\mathrm{nf2}} \cdot D_{\mathrm{nf}}\right), \qquad (3)$$

$$\mathrm{Su}_{\mathrm{ff}} = \mathrm{Su}_{\mathrm{factor}} \cdot \left(E_{\mathrm{ff}} \cdot H_{\mathrm{ff}} \cdot \mathrm{LC}_{\mathrm{ff1}} \cdot \mathrm{LC}_{\mathrm{ff2}} \cdot \mathrm{Seg}_{\mathrm{ff}} \cdot D_{\mathrm{nf}} \cdot \mathrm{Sep}_{\mathrm{ff}}\right). \qquad (4)$$

Subsequently, the overall exposure is estimated by algorithm equation (5):

$$C_t = \frac{1}{t_{\mathrm{total}}} \sum_{\mathrm{tasks}} \left\{ t_{\mathrm{exposure}} \cdot \left(C_{\mathrm{nf}} + C_{\mathrm{ff}} + \mathrm{Su}\right) \right\} + t_{\mathrm{non\text{-}exposure}} \cdot 0. \qquad (5)$$

The algorithm considers multiple activities [and exposure time (t_{exposure})] within an 8-h work shift (t_{total}) and also allows periods with assumingly zero exposure ($t_{\mathrm{non\text{-}exposure}}$).

Table 1. Description of principal modifying factors (MF) (from Tielemans *et al.*, 2008)

Principal modifying factor (MF)	Description
Substance emission potential (E)	Determines the intrinsic emission potential of a substance (e.g. dustiness for particulate agents and volatility for liquids).
Activity emission potential (H)	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).
Localized controls (LC)	Control measures in close proximity of the source intended to remove emissions (e.g. LEV, wet suppression techniques).
Segregation	Isolation of sources from the work environment without containment of the source itself (e.g. separate drying room).
Dispersion (dilution)	Natural and mechanical ventilation characteristics, determining the dilution of air contaminants through the room, i.e. between NF–FF zone and FF outside.
Personal enclosure (separation)	Providing a worker with a personal enclosure within a work environment (e.g. air conditioned cabin).
Surface contamination and fugitive emissions	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) and unintended and unpredictable leaks from process equipment.

The algorithms are based on the assumption that the near- and far-field exposures occur in the same work area. In addition, the equations apply to situations where operational conditions remain stable, and it can therefore not account for variable source strengths within one activity. The model allows for only one (main) source in the near- or far-field, and an additional source in the far-field can be added when the main source is located in the near-field.

Although we strived to assign multipliers that approximated a quantitative exposure estimate, the mechanistic model is dimensionless and gives a relative exposure score for the geometric mean (GM) of an exposure scenario. Calibration of the mechanistic model was performed using a comprehensive exposure database collated from various sources in different countries covering multiple scenarios and substances. Stringent data quality guidelines were applied: i.e. information on all MF of the mechanistic model should be available for all tasks conducted during the measurement. Mixed-effects regression models were used to evaluate the association between model scores and measurements, with stratified analyses for different exposure forms: abrasive dust, inhalable dust, vapours, and mist (liquid aerosols). These statistical analyses also provided information on the uncertainty of the mechanistic model estimates. The calibration of the mechanistic model is described in more detail by Schinkel *et al.* (2011).

CHARACTERIZATION OF PRINCIPAL MFs

Various sources were used to assign numerical values to the multipliers of each MF. These numeric values reflect a 'typical' (i.e. median) value of a theoretical distribution for each MF. A logarithmic scale was used because personal exposure levels are commonly found to be log-normally distributed. The evidence used to underpin this assessment procedure was, where possible, based on chemical and physical laws (e.g. weight fraction) and knowledge on substance behaviour (e.g. Raoult's law). Where this was not possible, empirical data obtained from literature were used to allocate multipliers. The Exposure Control Efficacy Library (ECEL) (Fransman *et al.*, 2008) in conjunction with expert judgement was used for the underpinning of the assigned model multipliers (Table 2).

Multipliers for all MF were peer reviewed by leading experts from industry, research institutes, and public authorities across the globe. In addition, several workshops with experts were organized to discuss the proposed exposure multipliers for different MF. Based on this comprehensive peer review process, a consensus view was developed, resulting in a list of final multipliers for all the principal MF.

Nine principal MFs have been proposed in the ART conceptual model (Tielemans *et al.*, 2008), of which seven will be discussed in this paper (excluding 'worker behaviour' and 'RPE'). The assumption is that all these MFs are mutually independent, and therefore, a transparent distinction between the MF is required. Table 1 gives an overview of the seven MF and their definitions. The following sections give an overview of the characterization of each MF, focusing on the classification of parameters and the assignment of multipliers.

Substance emission potential

Emission of chemical agents in the workplace occurs mainly by evaporation of (volatile) liquids or by release of aerosols from solid materials resulting in a dust or (non- or low-volatile) liquids resulting in a mist. Different intrinsic properties of a product are relevant in terms of emission by evaporation (i.e. vapour pressure) or particle release (i.e. dustiness). The following categories for modelling substance emission potential were identified that apply for handling:

- Solid objects (resulting in dust exposure)
- Powders and granules (resulting in dust exposure)
- Volatile liquids (resulting in vapour exposure)
- Low-volatile liquids (resulting in mist exposure)

Each of these categories has a distinct set of underlying determinants that were used for modelling 'substance emission potential' (Table 2), which are described below. More details on the scientific background information of modelling substance emission potential are described by Martie van Tongeren *et al.* (2011).

Solid objects. Little is known about the intrinsic properties of solid material and how it determines dust release during abrasive techniques. A few studies touch on this topic with respect to handling wood and stone, which suggest that 'hardness' of the material is important. However, as there is so little empirical evidence with respect to the impact of the type of material on exposure levels, we have not introduced multipliers for intrinsic emission potential of solid objects and it is assumed that this characteristic is (at least partially) captured in the 'activity emission potential' component of the model (see next section).

Increasing the moisture content of a solid object prior to the activity can reduce the exposure potential.

Table 2. ART model scoring for each modifying factor (excluding activity emission potential)

Substance/exposure type	Relevant exposure parameters/ classification of modifying factor	ART model classification	Multiplier
Substance emission potential (E)			
Solid objects	Intrinsic emission	—	
	Moisture contents	Dry product	1.0
		5–10% moisture	0.3
		>10% moisture	0.03
	Weight fraction	Exact weight fraction or categories	
Powders and granules	Dustiness	Measured dustiness (mg/kg) or Extremely fine and light powder	1.0
		Fine dust	0.3
		Coarse dust	0.1
		Granules, flakes, or pellets	0.03
		Firm granules, flakes, or pellets	0.01
	Moisture contents	Dry product	1.0
		5–10% moisture	0.1
		>10% moisture	0.01
	Weight fraction	Exact weight fraction or categories	
Volatile liquids (vapours)[a]	Process temperature	Exact temperature or categories	
	Vapour pressure at process temperature	Exact vapour pressure or (if unknown) vapour pressure calculated based on the boiling point temperature and the process temperature.	
	Mol fraction	Exact mol fraction or categories	
	Activity coefficient	Exact activity coefficient or select from predefined list.	
Low-volatile liquids (mists)[b]	Viscosity	Low viscosity (like water)	1.0
		Medium viscosity (like oil)	0.3
	Weight fraction	Exact weight fraction or categories	
Activity emission potential	See Tables 3–5		
Localized controls			
All substance types	No localized controls	No localized controls	1.0
	Suppression techniques	Wetting at the point of release	0.1
		Knockdown suppression	0.7
	Containment—no extraction	Low-level containment	0.1
		Medium-level containment	0.01
		High-level containment	0.001
	Local ventilation systems—receiving hoods	Canopy hoods	0.5
		Other receiving hoods	0.2
	Local ventilation systems—capturing hoods	Fixed capturing hoods	0.1
		Movable capturing hoods	0.5
		On-tool extraction	0.1
	Local ventilation systems—enclosing hoods	Fume cupboard	0.01
		Horizontal/downward laminar flow booth	0.1
		Other enclosing hoods	0.1
	Local ventilation systems—other LEV systems	Other LEV systems	0.5

Table 2. *Continued*

Substance/exposure type	Relevant exposure parameters/ classification of modifying factor	ART model classification	Multiplier
	Glove bags and glove boxes	Glove bag (non-ventilated)	0.01
		Glove bag (ventilated or kept under negative pressure)	0.001
		Low-specification glove box	0.001
		Medium-specification glove box	0.0003
		High-specification glove box	0.0001
	Vapour recovery systems	Vapour recovery systems	0.2
Segregation			
All substance types	Complete or partial segregation	No segregation	1.0
	Ventilation of the segregated area Filtration of recirculated air	Partial segregation without ventilation	0.7
		Partial segregation with ventilation and filtration of recirculated air	0.3
		Complete segregation without ventilation	0.3
		Complete segregation with ventilation and filtration of recirculated air	0.1
Personal enclosure			
All substance types	Complete or partial enclosure	No personal enclosure	1.0
	Ventilation of the personal enclosure Positive pressure inside the personal enclosure	Partial personal enclosure without ventilation	0.7
		Partial personal enclosure with ventilation	0.3
		Complete personal enclosure without ventilation	0.3
		Complete personal enclosure with ventilation	0.1
Surface contamination and fugitive emissions			
All substance types	Housekeeping practices	Default level	0.01
	Maintenance of machinery	General good housekeeping practices	0.003
	Use of protective clothing that repels spills	Demonstrable and effective housekeeping practices	0.001
		Process fully enclosed (air tight)	0
Dispersion—indoors			
Vapours	Room volume (30–3000 m^3)	Near field sources:	
	Air changes per hour (0.3–30 ACH)	From 'room volume = 3000 m^3, 30 ACH' to 'room volume = 30 m^3, 0.3 ACH'	1.0–36
		Far field sources:	
		From 'room volume = 3000 m^3, 30 ACH' to 'room volume = 30 m^3, 0.3 ACH'	0.01–35
Dusts and mists	Room volume (30–3000 m^3)	Near field sources:	
	Air changes per hour (0.3–30 ACH)	From 'room volume = 3000 m^3, 30 ACH' to 'room volume = 30 m^3, 0.3 ACH'	0.7–6.3
		Far field sources:	0.004–5.7
		From 'room volume = 3000 m^3, 30 ACH' to 'room volume = 30 m^3, 0.3 ACH'	

Table 2. *Continued*

Substance/exposure type	Relevant exposure parameters/ classification of modifying factor	ART model classification	Multiplier
Dispersion—outdoors			
Vapours	Distance of the source from buildings Distance of the source from the worker	Near field sources:	
		Close to buildings	1
		Far from buildings	0.3
		Far field sources (1–4 m from worker):	
		Close to buildings	0.03
		Far from buildings	0.01
		Far field sources (>4 m from worker):	
		Close to buildings	0.01
		Far from buildings	0.003
Dusts and mists	Distance of the source from buildings Distance of the source from the worker	Near field sources:	
		Close to buildings	0.75
		Far from buildings	0.2
		Far field sources (1–4 m from worker):	
		Close to buildings	0.015
		Far from buildings	0.005
		Far field sources (>4 m from worker):	
		Close to buildings	0.005
		Far from buildings	0.00167
Dispersion—unidirectional room airflow			
Vapours	Spray rooms	Cross-flow spray room	1.0
		Down-flow spray room	0.3
	Downward laminar flow booths	Downward laminar flow booth and no screens	0.3
		Downward laminar flow booth using partial screen	0.2
		Downward laminar flow booth using partial screen fitted with glove ports	0.15
		Downward laminar flow booth using full screen fitted with glove ports	0.015
Dusts and mists	Spray rooms	Cross-flow spray room	0.7
		Down-flow spray room	0.2
	Downward laminar flow booths	Downward laminar flow booth and no screens	0.2
		Downward laminar flow booth using partial screen	0.15
		Downward laminar flow booth using partial screen fitted with glove ports	0.1
		Downward laminar flow booth using full screen fitted with glove ports	0.01

[a] Substance emission potential of volatile liquids is calculated by E = (vapour pressure at process temperature × mol fraction × activity coefficient)/30 000. If the vapour pressure at process temperature is unknown, it can be calculated based on the boiling point temperature by using: vapour pressure = 101 000 × $e^{(-10.6 \times ((\text{boiling point temperature (in K)}/\text{process temperature (in K)})-1)}$.

[b] Substance emission potential of low-volatile liquids is calculated by E = (10/30 000) × weight fraction × viscosity.

Wetting (wetness) of a substance (powder/granule) or solid object (e.g. wood) prior to an activity (e.g. wetting before sweeping) is considered to be part of the substance emission potential and the 'moisture' or 'moistness' of the product is assessed. Where wetting takes place during or after emission of a substance (e.g. wetting at the point of emission), it refers to 'suppression', which is a localized control and not addressed in the substance emission potential.

We propose three categories of moisture content: dry product, some moisture (5–10% moisture content) in or on the objects, and >10% moisture content (Table 2). Since there was little empirical evidence on the effect of adding moisture to solid objects, it was assumed that (because of the physical properties of solid objects) increasing the moisture content for solid objects is not as effective in reducing dust concentrations as it is for powders/granules (see next section). Furthermore, it is assumed that the substance emission potential is proportional to the weight fraction of the substance of interest in the solid object (in case, the substance is homogenous in the object).

Powders and granules. Dustiness is an important parameter that is characterized as the propensity of materials to produce airborne dust during handling (Mark, 2005). Hjemsted and Schneider (1996) conducted a comprehensive review of studies that evaluated dustiness of substances and found that test results are sometimes ambiguous and often inconclusive. Parameters that may have an impact on dustiness are the fraction of fine particles, heterogeneity of the size distribution, shape of particles, bulk density, moisture content, and friability. Although the dustiness of some powders and granules has been quantitatively measured (Pensis *et al.*, 2010), a qualitative evaluation is typically used in exposure assessment tools (HSE, 1999; Marquart *et al.*, 2008). We propose a dustiness classification on a categorical scale with five classes (Table 2). A range of two orders of magnitude between the lowest and highest dustiness class appears to be plausible given the total range in individual dustiness test results (Martie van Tongeren *et al.*, 2011).

Similar to solid objects, we propose three categories of moisture content for powders and granules. Increasing the moisture content may reduce dustiness of one order of magnitude or more (Leith, 1991), and thus, a reduction factor of 0.1 is adopted in the proposed scheme. Experimental tests have shown that applying large amounts of water may reduce exposure with ~99% compared to baseline (Thorpe *et al.*, 1999) and therefore, a category with a multiplier equal to 0.01 was introduced. Furthermore, it is assumed that the substance emission potential is proportional to the weight fraction of the substance of interest in the powdered or granulized product (in case, the substance is homogenous in the powder/granule).

Volatile liquids (vapours). For liquids, the process of emission takes place through mist formation (described in the next section), evaporation, or both. Nielsen *et al.* (1995) have shown that the evaporation rate increases proportionally with vapour pressure, which increases exponentially with the temperature of the liquid. In case of a mixture of liquids, all substances in the mixture will contribute to the overall vapour pressure and therefore, a correction factor is introduced into Raoult's law that corrects for interactions between the components' molecules in solution (Martie van Tongeren et al., 2011). The intrinsic emission potential for volatile substances in the ART model is calculated within the limits 10 and 30 000 Pa. Liquids with vapour pressures <10 Pa mainly lead to exposure based on mist release. Liquids with very high vapour pressures (>30 000 Pa) start to behave like gases and the relation between vapour pressure and emission is no longer believed to be linear. Liquids with extremely high vapour pressures (>100 000 Pa) are considered to be gases, which are not (yet) included in the ART model.

Low-volatile liquids (mists). Handling of low-volatile liquids (i.e. vapour pressure ≤10 Pa) can result in exposure to mist, which is mainly determined by the activity that is performed. The effects of intrinsic properties of liquids on mist release are not extensively documented in the scientific literature. The only intrinsic property that is considered to affect the potential for mist formation is the viscosity of the product (Table 2). The weight fraction of the chemical substance in the product is assumed to be proportional to the emission of the chemical (i.e. a 10% content of the chemical substance in the product gives a 10 times lower emission than a pure substance). This category of substance emission potential also includes powders dissolved in a liquid matrix (e.g. copper powder in antifouling paint).

Activity emission potential

The classification of occupational activities for assessment of inhalation exposure is described elsewhere (Marquart *et al.*, 2011). Activity emission potential categories are defined for each substance type (solid objects, powders, and liquids) and for each activity (sub)class and the range of multipliers may differ between activity (sub)classes (Tables 3–5). A predefined list of exposure multipliers (on a logarithmic scale from 0.001 to 100) was used to determine the activity emission potential.

Multipliers for activity emission potential for each activity (sub)class were obtained by comparing results of exposure measurements from different measurement series described in published literature and our own archives. Exposure data were not available for each activity class, in which case multipliers were assigned by interpolation based on the available evidence in other activity classes and by using expert judgements. A description of the exposure studies that were used to underpin the activity emission potential multipliers (Tables 3–5) is available on the ART website (www.advancedreachtool.com).

Activity classes associated with solid objects. This category includes wood and stone (and in the future other materials might be added as well) and describes 'fracturing and abrasion' and 'abrasive blasting' (Table 3). The technique is probably a good proxy parameter that describes a number of (combined) determinants for exposure intensity, including energy input, transmission of forces from tool to surface, and surface area fractured or abraded. Also, the particle size emitted depends on the applied technique and force. All these parameters are to a large extent interlinked and therefore, a general categorization of 'technique class' is proposed that differentiates between these activities (Table 3).

For fracturing wood, a maximum multiplier of 30 was assigned based on task-based exposure measurements in the construction industry which showed maximum values for inhalable dust of ~30 mg m^{-3} (Spee *et al.*, 2007). The exposure levels associated with fracturing stone were considered to be higher than those for wood, and a maximum exposure multiplier of 100 was assigned (Table 3).

For abrasive blasting, the exposure level depends on the surface being blasted (i.e. concentration of contaminant in coating), the abrasive media used (dry or wet), the blasting technique, and the direction of blasting (Table 3). Limited data were available on abrasive blasting, and therefore, predominantly expert judgements were made to allocate relative values to different techniques.

Activity classes associated with powders and granules. Seven activity classes are distinguished for powders and granules (Table 4). The most important determinants of exposure from 'impaction on contaminated solid objects' and 'handling of contaminated solid objects or paste' are the level of contamination of the surface or object and the amount of energy applied to the surface or object during impaction or handling. With regard to powder coating, Llewellyn *et al.* (1996) indicated that spraying in an upward direction results in significantly higher exposure than spraying in a downward or horizontal direction. The most important determinants for exposure from 'movement and agitation of powders/granules' are the amount of substance, the amount of energy applied to it, and the level of process containment. The emission during the subclass 'falling powder' is mainly driven by falling height, use rate, the type of transfer, and the process containment. The increase in aerosol concentration is less than proportional to the falling mass, probably because most of the aerosols are generated from the front of the product stream (Plinke *et al.*, 1991; Heitbrink *et al.*, 1992; Ansart *et al.*, 2009). It is therefore assumed that a disproportional increase of emission (with a factor of 3) can be expected with each order of magnitude increase in mass. Drop height was arbitrarily dichotomized into two categories (<0.5 m and ≥ 0.5 m). Furthermore, aerosol generation can be reduced by careful handling and by minimizing the contact between falling powder and air (Heitbrink *et al.*, 1992). Determinants for exposure from the activity classes 'compressing of powders/granules' and 'fracturing of powders/granules' are the amount of product that is compressed or fractured and the level of process containment.

Activity classes associated with (volatile and low-volatile) liquids. A distinction was made between six different activity classes relevant for liquids (Table 5). Multipliers for exposure determinants were assigned separately for vapour and mist exposure since completely different exposure mechanisms are relevant for both types of exposure (evaporation versus aerosol formation). Pressure, use rate, spray technique, and the direction of spraying were considered important parameters for 'spray application of liquids'. Several studies showed that spraying of high application volumes per time unit led to an increase in inhalable exposure levels and that high pressure spraying and fogging of biocides results in much higher exposure levels than low pressure application techniques (differences of one order of magnitude or more were found) (Machera *et al.*, 2003; Berger-Preiss *et al.*, 2005). Overhead spraying causes approximately three times higher inhalation exposure levels as compared to downward or horizontal directions (Berger-Preiss *et al.*, 2005). For 'activities with relatively undisturbed surfaces (no mist formation)', the published exposure levels give an indication that surface area is important (McCammon *et al.*, 1991; von Grote *et al.*, 2006). Based on these studies, a range of exposure multipliers from 0.003 to 0.3 was proposed

Table 3. Parameters and range of inputs for 'activity emission potential' of solid objects scenarios (the overall multiplier for activity emission potential is calculated by multiplying the multipliers for separate parameters)

Activity class	Activity subclass	Description	Parameter[a]	Range of inputs[b] and model scoring	Multiplier
Fracturing and abrasion of solid objects		Activities where solid objects are broken into smaller parts or are abraded due to frictional forces (e.g. crushing, sawing, sanding)	Type of material	Wood and stone	—
			Type of handling, amounts of dust and size of object	Wood:	
				Mechanical sanding of wood resulting in large amounts of dust	30
				Mechanical handling of wood resulting in large amounts of dust (e.g., large speed of moving work pieces or rotating cutting blades)	10
				Mechanical handling of wood resulting in limited amount of dust	3
				Manual handling of wood resulting in limited amount of dust	3
				Manual handling of wood resulting in very limited amount of dust	0.3
				Stone:	
				Mechanical pulverization of large amounts of stone or large objects	100
				Mechanical treatment/abrasion of large surfaces	100
				Mechanical treatment/abrasion of small sized surfaces	30
				Mechanical pulverization of stones	10
				Manual pulverization or treatment/abrasion of small sized objects	3
				Careful breaking stones	0.3
			Level of containment of the process (wood and stone)	Open process	1.0
				Handling that reduces contact between product and adjacent air.	0.3
Abrasive blasting		A surface preparation technique for removing coatings or contamination by propelling abrasive material towards the surface at high velocity (e.g. grit blasting). ART only considers exposure arising from the surface coatings during abrasive blasting (i.e. exposure to the abrasive material is not included)	Surface area treated	Abrasive blasting of very large surfaces	100
				Abrasive blasting of large surfaces	30
				Abrasive blasting of small parts	10
				Micro-abrasive blasting	1
			Wet or dry blasting	Dry abrasive blasting	1
				Wet abrasive blasting	0.3
			Direction of blasting	Abrasive blasting in any direction (inclination upwards)	3
				Only downward blasting	1
				Only downward blasting	0.3

[a] Parameters are presented in ART in the form of questions. In some cases, questions contain more than one parameter, for example in the case of 'Fracturing and abrasion of solid objects'. The total multiplier for each MF is a multiplication of the multipliers for the different parameters per MF.

[b] In some cases, the input options are presented in an abbreviated form.

Table 4. Parameters and range of inputs for 'activity emission potential' of powders and granules scenarios (the overall multiplier for activity emission potential is calculated by multiplying the multipliers for separate parameters)

Activity class	Activity subclass	Description	Parameter[a]	Range of inputs[b] and model scoring	Multiplier
Impaction on contaminated solid objects		Activities where impaction or striking of a tool on an object contaminated with powder or granules potentially results in re-suspension of that powder (e.g. hammering, punching). For this activity class, exposure is estimated to be related to the level of contamination on the surface or the object that is impacted on.	Level of contamination	Impaction on substantially and visibly contaminated objects (layers of $>$ 0.5 kg).	3
				Impaction on objects with visible residual dust	1
				Impaction on objects with limited visible residual dust	0.3
				Impaction on slightly contaminated (layers of less than few grams) objects	0.1
				Impaction on apparently clean objects	0.001
			Force of impaction	Normal impaction (manual or light mechanical)	1
				Heavy mechanical impaction	3
Handling of contaminated solid objects or paste		Handling or transport of surfaces, objects, or pastes that are (potentially) contaminated with powders or granules (e.g. sorting, stacking, plastering). For this activity class, exposure is estimated to the contamination on the surface, object, or paste.	Level of contamination	Handling of substantially and visibly contaminated objects (layers of $>$ 0.5 kg).	1
				Handling of objects with visible contamination (object covered with fugitive dust from surrounding dusty activities)	0.3
				Handling of objects with limited residual dust (thin layer visible)	0.1
				Handling of slightly contaminated (layers of less than few grams) objects	0.03
				Handling of apparently clean objects	0.001
			Carefulness of handling	Careful handling	0.3
				Normal handling	1
				Handling that departs from regular work procedures and involves large amounts of energy	3
Spray application of powders		Spraying activities used to intentionally disperse powders on surfaces by using a pressure difference (e.g. dusting crops, powder coating).	Type of application	Powder coating	10
				Dusting using blower	3
			Direction of application	Any direction (including upwards)	3
				Only horizontal or downwards	1
				Only downwards	0.3

Table 4. *Continued*

Activity class	Activity subclass	Description	Parameter[a]	Range of inputs[b] and model scoring	Multiplier
Movement and agitation of powders, granules, or pelletized material		Activities where movement and agitation of powders results in disturbances of the product causing dust particles to become airborne (e.g. sweeping, mixing, sieving).	Amount of product	Movement and agitation of $\geq$1000 kg	30
				Movement and agitation of 100–1000 kg	10
				Movement and agitation of 10–100 kg	3
				Movement and agitation of 1–10 kg	1
				Movement and agitation of 0.1–1 kg	0.3
				Movement and agitation of 10–100 g	0.1
				Movement and agitation of $<$10 g	0.03
			Level of agitation	Application of compressed air	30
				Other handling with high level of agitation	3
				Handling with low level of agitation	1
			Level of containment of the process	Open process	1
				Handling that reduces contact between product and adjacent air	0.3
Transfer of powders, granules, or pelletized material	Falling of powders	Activities where a stream of powder is transferred from one reservoir (or container, vessel) to the receiving vessel. The product may either fall due to gravity from a high to a lower point (e.g. dumping of powders), be transferred horizontally (e.g. scooping of powders) or is transferred through a hose or tube with pressure (e.g. vacuum transfer).	Use rate	Transferring $>$1000 kg min^{-1}	30
				Transferring 100–1000 kg min^{-1}	10
				Transferring 10–100 kg min^{-1}	3
				Transferring 1–10 kg min^{-1}	1
				Transferring 0.1–1 kg min^{-1}	0.3
				Transferring 10–100 g min^{-1}	0.1
				Transferring $<$10 g min^{-1}	0.03
			Carefulness of handling	Routine transfer	1
				Careful transfer	0.3
			Drop height	Drop height $\geq$0.5 m	3
				Drop height $<$0.5 m	1
			Level of containment of the process	Open process	1
				Handling that reduces contact between product and adjacent air	0.3
	Vacuum transfer of powders		Use rate	Transferring $>$1000 kg min^{-1}	3
				Transferring 100–1000 kg min^{-1}	1
				Transferring 10–100 kg min^{-1}	0.3
				Transferring 1–10 kg min^{-1}	0.1
				Transferring 0.1–1 kg min^{-1}	0.03
				Transferring 10–100 g min^{-1}	0.01
				Transferring $<$10 g min^{-1}	0.003
			Level of containment of the process	Open process	1
				Handling that reduces contact between product and adjacent air	0.3

Table 4. *Continued*

Activity class	Activity subclass	Description	Parameter[a]	Range of inputs[b] and model scoring	Multiplier
Compressing of powders, granules, or pelletized material		Activities where powders, granules, or pelletized material are compressed due to compaction or crushing (e.g. tabletting, rolling).	Use rate	Compressing >1000 kg min^{-1}	30
				Compressing 100–1000 kg min^{-1}	10
				Compressing 10–100 kg min^{-1}	3
				Compressing 1–10 kg min^{-1}	1
				Compressing 0.1–1 kg min^{-1}	0.3
				Compressing 10–100 g min^{-1}	0.1
				Compressing <10 g min^{-1}	0.03
			Level of containment of the process	Open process	1
				Handling that reduces contact between product and adjacent air	0.3
Fracturing of powders, granules, or pelletized material		Activities where powders, granules, or pelletized material are crushed and broken into smaller parts or sizes due to frictional forces (between two surfaces or objects; e.g. grinding minerals)	Use rate	Fracturing > 1000 kg min^{-1}	30
				Fracturing 100–1000 kg min^{-1}	10
				Fracturing 10–100 kg min^{-1}	3
				Fracturing 1–10 kg min^{-1}	1
				Fracturing 0.1–1 kg min^{-1}	0.3
				Fracturing 10–100 g min^{-1}	0.1
				Fracturing <10 g min^{-1}	0.03
			Level of containment of the process	Open process	1
				Handling that reduces contact between product and adjacent air	0.3

[a] Parameters are presented in ART in the form of questions. In some cases, questions contain more than one parameter, for example in the case of ‘Fracturing of powders, granules, or pelletized material’. The total multiplier for each MF is a multiplication of the multipliers for the different parameters per MF.

[b] In some cases, the input options are presented in an abbreviated form.

Table 5. Parameters and range of inputs for 'activity emission potential' of liquid scenarios (the overall multiplier for activity emission potential is calculated by multiplying the multipliers for separate parameters)

Activity class	Activity subclass	Description	Parameter[a]	Range of inputs[b] and model scoring	Multiplier mists	Multiplier vapours
Spray application of liquids	Surface spraying of liquids	Activities used to atomize liquids into droplets for dispersion on surfaces (surface spraying; e.g. paint spraying, pest control operations) or into air (space spraying; e.g. fogging, fly spray). Spraying techniques may be used for dispersion of e.g. pesticides, biocides, and paints.	Use rate	High application rate (>3 l min^{-1})	3	3
				Moderate application rate (0.3–3 l min^{-1})	1	1
				Low application rate (0.03–0.3 l min^{-1})	0.3	0.3
				Very low application rate (<0.03 l min^{-1})	0.1	0.1
			Direction of application	Any direction (including upwards)	3	3
				Only horizontal or downwards	1	1
				Only downwards	0.3	0.3
			Spray technique	Spraying with high compressed air use	3	3
				Spraying with no or low compressed air use	1	1
	Spraying of liquids in a space		Scale of application	Large scale space spraying	10	10
				Small scale space spraying	1	1
Activities with open liquid surfaces and open reservoirs	Activities with relatively undisturbed surfaces (no aerosol formation)	Handling of a liquid product in a bath or other reservoir. The liquid may either be relatively undisturbed (e.g. manual stirring, dipping in bath) or agitated (e.g. gas bubbling, mechanical mixing in vessel, electroplating).	Open surface area	Open surface >3 m^2	0.001	0.3
				Open surface 1–3 m^2	0.001	0.1
				Open surface 0.3–1 m^2	0.001	0.03
				Open surface 0.1–0.3 m^2	0.001	0.01
				Open surface <0.1 m^2	0.001	0.003
	Activities with agitated surfaces		Open surface area	Open surface >3 m^2	0.3	1.0
				Open surface 1–3 m^2	0.1	0.3
				Open surface 0.3–1 m^2	0.03	0.1
				Open surface 0.1–0.3 m^2	0.01	0.03
				Open surface <0.1 m^2	0.003	0.01

Table 5. *Continued*

Activity class	Activity subclass	Description	Parameter[a]	Range of inputs[b] and model scoring	Multiplier mists	Multiplier vapours
Handling of contaminated objects		Handling of solid objects that are treated or contaminated with the liquid of interest (e.g. handling of contaminated tools, evaporation from painted surface).	Contaminated surface area	Activities with treated/contaminated objects (surface $> 3\ \mathrm{m}^2$)	0.001	0.3
				Activities with treated/contaminated objects (surface $1\text{–}3\ \mathrm{m}^2$)	0.001	0.1
				Activities with treated/contaminated objects (surface $0.3\text{–}1\ \mathrm{m}^2$)	0.001	0.03
				Activities with treated/contaminated objects (surface $0.1\text{–}0.3\ \mathrm{m}^2$)	0.001	0.01
				Activities with treated/contaminated objects (surface $<0.1\ \mathrm{m}^2$)	0.001	0.003
			Level of contamination	Contamination >90% of surface	1	1
				Contamination 10–90% of surface	0.3	0.3
				Contamination <10% of surface	0.1	0.1
Spreading of liquid products		Activities where liquid products are spread onto a surface (e.g. painting a ceiling/wall with roller or brush, laminating)	Scale of application	Spreading of liquids at surfaces or work pieces $>3\ \mathrm{m}^2\ \mathrm{h}^{-1}$	0.1	0.3
				Spreading of liquids at surfaces or work pieces $1.0\text{–}3.0\ \mathrm{m}^2\ \mathrm{h}^{-1}$	0.1	0.1
				Spreading of liquids at surfaces or work pieces $0.3\text{–}1.0\ \mathrm{m}^2\ \mathrm{h}^{-1}$	0.1	0.03
				Spreading of liquids at surfaces or work pieces $0.1\text{–}0.3\ \mathrm{m}^2\ \mathrm{h}^{-1}$	0.01	0.01
				Spreading of liquids at surfaces or work pieces $<0.1\ \mathrm{m}^2\ \mathrm{h}^{-1}$	0.001	0.003
Application of liquids in high speed processes (e.g. rotating tools)		High energy activities with e.g. rotating tools where liquids are added to the process (e.g. metal working fluids).	Scale of application	Large-scale activities involving high speed movements	3	3
				Small-scale activities involving high speed movements	1	1
			Level of containment of the process	Open process	1	1
				Handling that reduces contact between product and adjacent air	0.3	0.3

Table 5. *Continued*

Activity class	Activity subclass	Description	Parameter[a]	Range of inputs[b] and model scoring	Multiplier mists	Multiplier vapours
Transfer of liquid products	Bottom loading	Activities where a stream of liquid product is transferred from one reservoir to the next. The stream may either fall or glide from high to a lower point (falling liquids; e.g. filling of drums, tanker top loading) or is transferred with pressure (pressurized transfer: e.g. bottom loading).	Use rate	Transfer of liquid product with flow of >1000 l min^{-1}	0.001	0.1
				Transfer of liquid product with flow of 100–1000 l min^{-1}	0.001	0.03
				Transfer of liquid product with flow of 10–100 l min^{-1}	0.001	0.01
				Transfer of liquid product with flow of 1–10 l min^{-1}	0.001	0.003
				Transfer of liquid product with flow of 0.1–1 l min^{-1}	0.001	0.001
				Transfer of liquid product with flow of <0.1 l min^{-1}	0.001	0.001
	Falling liquids		Use rate	Transfer of liquid product with flow of >1000 l min^{-1}	0.1	0.1
				Transfer of liquid product with flow of 100–1000 l min^{-1}	0.03	0.03
				Transfer of liquid product with flow of 10–100 l min^{-1}	0.01	0.01
				Transfer of liquid product with flow of 1–10 l min^{-1}	0.003	0.003
				Transfer of liquid product with flow of 0.1–1 l min^{-1}	0.001	0.001
				Transfer of liquid product with flow of <0.1 l min^{-1}	0.001	0.001
			Level of containment of the process	Open process	1	1
				Handling that reduces contact between product and adjacent air	0.3	0.3
			Type of application	Splash loading	3	3
				Submerged loading	1	1

[a] Parameters are presented in ART in the form of questions. In some cases, questions contain more than one parameter, for example in the case of 'Application of liquids in high speed processes'. The total multiplier for each MF is a multiplication of the multipliers for the different parameters per MF.

[b] In some cases. the input options are presented in an abbreviated form.

for vapour exposure depending on surface area in contact with the air. For agitated surfaces, the proposed multipliers for vapours are a factor 3 higher as compared to activities with undisturbed reservoirs. As expected, the exposure to mists is lower in these types of activities than exposure to vapours (Bright *et al.*, 1997; Kiilunen *et al.*, 1997; Makinen and Linnainmaa, 2004). Mist exposure from undisturbed baths was assumed to be very low and independent of surface area. Very limited published exposure levels were available for the activity class 'handling of contaminated objects'. Therefore, the exposure multipliers were chosen in line with 'activities with relatively undisturbed surfaces' with an additional determinant covering the level of contamination. The treated surface area appears to be the most important determinant of exposure for 'spreading of liquid products' (Ludersdorf *et al.*, 1985; Geuskens *et al.*, 1992; Nylander-French *et al.*, 1999; Hertsenberg *et al.*, 2007). An important determinant for mist formation during 'application of liquids in high speed processes' is the speed of the tools (Heitbrink *et al.*, 2000), although the exact rotating speed of the tools will often be unknown in a generic assessment. Based on the information from published literature (Hendricks *et al.*, 1962; Casey *et al.*, 1983; Leon *et al.*, 1994; Hands *et al.*, 1996; Ross *et al.*, 2004; Park *et al.*, 2005, 2007; Steinsvag *et al.*, 2006; Lillienberg *et al.*, 2008; Suuronen *et al.*, 2008), it is not possible at this stage to distinguish between low- and high-speed machines. However, it appears reasonable to assign a multiplier of 3 for larger scale activities involving high-speed movement like a large rotating press. In addition, an exposure multiplier of 0.3 was assigned for processes that are (partially) contained to reduce contact between product and adjacent air.

During processes within the activity class 'falling liquids', the liquids may interact with air, inducing air currents in and around the stream, and result in release of vapour from the stream. Subsequently, the liquid may impact on the receiving surface, which will also lead to increased interaction with air and hence release of droplets (i.e. mists). Relevant determinants for the exposure emission during these activities are use rate and the opening of the receiving tank or bath, with a factor 3 difference between splash loading and submerged loading (Armstrong *et al.*, 1996; Fehrenbacher and Hummel 1996; Lewis *et al.*, 1997; Wolf *et al.*, 1999; Glass and Gray 2001). During bottom loading activities, we assume that there is very limited or no mist formation and that exposure mainly occurs through evaporation from residual liquids at the connection point and possible spills. Vapours may also be released via an opened manhole on top of the truck when a vapour recovery system is absent.

Localized controls

Localized controls are defined as engineering control measures in close proximity of the source, which are intended to contain and/or capture emitted contaminants from processes, machinery, and/or equipment before these are dispersed into the workplace air. Examples of localized control measures include suppression techniques, containment of the source, LEV systems, glove boxes/bags, and vapour recovery systems. Spray rooms (booths or cabins) can be considered as a particular form of enclosing hood. However, because both the worker and the source are located inside the spray room, we consider this type of control to be associated with room ventilation (unidirectional room airflow), which is included in the modifying factor 'dispersion'. It is important to note that the effectiveness of localized controls will often depend on worker behaviour and procedural elements (like work protocols, training, and maintenance). The proposed parameters and multipliers for different localized controls are presented in Table 2. Because some combinations of the described localized controls can be used simultaneously, the ART offers the possibility of selecting two localized controls (primary and secondary).

'Suppression' distinguishes between 'wetting at the point of release' during an activity (e.g. wet sawing or grinding), and 'knock-down' suppression where airborne contaminants are damped down in close proximity of the source. Wetting (wetness) of a substance (powder / granule) or solid object (e.g. wood) prior to an activity (e.g. wetting before sweeping) is considered to be part of the substance emission potential and the 'moisture' or 'moistness' of the product is assessed. Where wetting takes place during or after emission of a substance (e.g. wetting at the point of emission) it refers to 'suppression', which is a localized control and not addressed in the substance emission potential. Spray systems at transfer points and on material handling operations have been estimated to reduce emission by 70–95% (EPA, 1995; NIOSH, 2003). Water sprayed into the dust cloud (once it has become airborne) reduces airborne dust levels by no >30% (Courtney and Cheng, 1977) (Table 2).

'Containment' refers to isolation of the emission source by means of material barriers in the direct circumference of the source where a worker cannot enter (e.g. a lid on a bath). If complete containment is relied upon as the only method of control, it must be strong enough to remain dust or gas tight under all operational conditions unless proper provision is made to vent or release any excess pressure safely (BOHS, 1987). However, if the containment is not opened during the given activity or work shift, it can be an efficient way of minimizing levels of airborne contaminants. Partial containment without any form of local ventilation is not an effective way of reducing emission levels, with the effectiveness for partial enclosure ranging from 10 to 35% (Fransman *et al.*, 2008). Therefore, partial containment is not included as a separate (sub)class of localized controls. Three levels of containment were defined (Table 2): (i) low level containment (the process is contained with a loose lid or cover, which is not air tight), (ii) medium level containment (the material transfer is enclosed with the receiving vessel being docked or sealed to the source vessel), and (iii) high level containment (the substance is contained within a sealed and enclosed system and the material transfer is entirely enclosed with high containment valves).

'LEV' systems aim to capture, contain, or receive emitted airborne contaminants before dispersion into the workplace air. Local ventilation hood types can be divided in three types (HSE, 2008): (i) receiving hoods (that receive the contaminant cloud, which has a speed and direction that is usually process generated; e.g. a canopy hood over a hot process), (ii) capturing hoods [that generate sufficient airflow at and around the source to 'capture' and draw in the contaminant-laden air (fixed or moveable and include on-tool extraction)], and (iii) enclosing hoods (a combination of enclosure with LEV). Although glove boxes and glove bags are considered to be a form of enclosing hoods, for practical reasons and user friendliness of the ART model, we created a separate class for glove boxes and glove bags. Different types of glove boxes (low-specification glove box, medium-specification glove box, and high-specification glove box) and glove bags (non-ventilated, ventilated, or kept under negative pressure) were defined based on the effectiveness to reduce emission levels (Fransman, *et al.*, 2010). Different configurations of the mentioned types of LEV are proposed and assigned with multipliers ranging from 0.5 (canopy hoods) to 0.0001 (high specification glove box).

'Vapour control' is the process of collection and/or recovering the vapours from volatile liquids or gases so that they do not escape into the environment, which results in the passive transfer of the same volume of vapours back to the tank (Institute of Petroleum, 2000; Saarinen *et al.*, 2000). Based on an inventory and appraisal of existing RMMs for use in REACH registration of petroleum-based substances, the conclusion was drawn that vapour collection systems are very efficient in reducing exposure levels, with an estimated median effectiveness of 80%.

Segregation

Segregation of the source aims to isolate the emission source from the worker by means of material barriers, where the segregated area is big enough for the worker to be able to enter into (e.g. a separate room with the source). The efficacy of segregation has not been extensively studied in the occupational hygiene field (Fransman *et al.*, 2008). However, evidence from indoor environment research (e.g. tobacco smoke leakage from smoking rooms) was useful in estimating the effect of segregated work spaces on personal exposure levels (Liu *et al.*, 2001; Miller and Nazaroff, 2001; Ott *et al.*, 2003; Wagner *et al.*, 2004). These studies concluded that the most important factors for a segregated area to be effective in reducing personal exposure levels in adjacent rooms were (i) full floor-to-ceiling walls, (ii) no return air from the segregated area (with emission source) to adjacent work areas, (iii) exhaust from the segregated area to the outside (not to adjacent areas), and (iv) to maintain a negative pressure in the segregated area compared with adjacent areas (Liu *et al.*, 2001; Wagner *et al.*, 2004). These studies showed a $\geq$90% reduction in contaminant concentration when comparing the contaminated room and the segregated room (Liu *et al.*, 2001; Miller and Nazaroff, 2001). The classification proposed for segregation considers either complete or partial segregation in combination with the presence or absence of ventilation (Table 2).

Personal enclosure

Personal enclosure (i.e. separation) provides a worker with an enclosure within a work environment (e.g. air-conditioned cabin). The concept of personal enclosure is similar to that of segregation, except that for personal enclosure not the source but the worker is placed in a separate area (e.g. cabin, room) within a work environment. Two critical components for an effective personal enclosure are proper design, installation and maintenance of filtration, and pressurization systems, along with a method for maintaining structural cab integrity (Cecala *et al.*, 2005). For a completely separated cabin, an extraction ventilation system can contribute to lower exposure levels especially when the incoming air is filtered (Bakke *et al.*, 2002; Rappaport *et al.*, 2003; Cecala *et al.*, 2005; NIOSH, 2007). In case of a partial personal enclosure, a major component in an effective system is to ensure that the enclosed cabin is positively air pressured, thereby preventing contaminated air from entering the personal enclosure (Cecala *et al.*, 2005). The efficacy of a complete personal enclosure with ventilation and effective filtration was estimated to be >90% (Cecala *et al.*, 2005; Fransman *et al.*, 2008). We propose a classification system for personal enclosure that considers both the level of enclosure (complete/partial) and the ventilation (Table 2).

Surface contamination and fugitive emissions

Apart from main (near-field and/or far-field) emission sources, emissions from contaminated surfaces arise from the evaporation of liquids or the resuspension of dusts following unintended and unpredictable leaks, spills, or other sources that have produced contamination on surfaces, such as work surfaces, floors, walls, clothing, tools, process equipment, and used rags. Exposure resulting from surface contaminants will not only be dependent on the substance emission potential of the contaminant (e.g. dustiness, volatility) but also the activity associated with the release (e.g. type of cleaning, housekeeping practices, maintenance practices). Some authors have proposed that since workers are actively resuspending dusts during their body movements and other activities, workers are enveloped in a ‘personal cloud’, which actively transports contaminants into the person’s breathing zone because of thermal convection from their body heat (Schneider, 2008). Spills of volatile liquids onto clothing will also contribute to personal exposure. Our assumption is that the emission from contaminated surfaces and fugitive sources will generally be small (<1%) in comparison with the contribution from active emission sources. These fugitive emission sources are assumed to be related to different configurations of housekeeping practices, maintenance of machinery, and the use of protective clothing that repels spills (Table 2).

Dispersion

Dispersion is dependent on turbulent diffusion and bulk air movement, either because of pressure differences in the room or because of thermal convection. Dispersion from a point source in a large workroom occurs mainly through turbulent diffusion, which can be explained by relatively simple theoretical models. However, dispersion through the workspace may not be uniform because the inlet air may not completely mix with the room air, which may be because of poor design of the inlet or exhaust systems or because of the complex geometry within the room. Parameters and multipliers are presented in Table 2 and more (technical) details on dispersion are described by Cherrie *et al.* (2011).

Indoor dispersion. A simple approach to modelling the concentration of a contaminant in indoor spaces was originally suggested by Hemeon (1963), where the room is subdivided into two compartments, separated by a virtual boundary through which air can be exchanged. Based on this approach, Cherrie (1999) investigated the relationship between the air concentration of a contaminant using a two-box model where one ‘box’ was located around the workers nose and mouth of side 2 m (designated the near-field) and the second box was the remainder of the room (designated the far-field). For developing the ART model, the simulations carried out by Cherrie (1999) were repeated with varying room sizes and air change rates and resulted in the multipliers presented in Table 2. The effect of deposition for various particle sizes was estimated using results from simulations carried out by Schneider *et al.* (1999). The results of these simulations provide us with multipliers for different room sizes and for different monodisperse aerosols.

Outdoor dispersion. The dispersion of contaminants outdoors is different from indoors because of the difference in boundaries to contain the pollutant in the vicinity of the worker. In addition, the strength of the wind will generally be higher than the turbulent airflows inside buildings. The dispersion of pollutants away from the source outdoors can be described by a simple Gaussian dispersion model. The plume is driven in the longitudinal direction by the wind and in the transverse directions by turbulent diffusion. In most scenarios, the orientation of the worker in relation to the source (and wind) will be impossible to assess, and it is therefore assumed that equal probability exists that the worker could be orientated at any angle to the wind. It is assumed that there are two situations outdoors where the scenario may be located: close to buildings or away from buildings or other obstructions. Workplaces with a roof and at least two solid walls, with the remaining sides open to the outdoor air, are considered to be indoor environments for the purpose of ART. If the worker is relatively close to the (outdoor) far-field source (1–4 m), it is suggested (based on expert judgement) that the far-field level should be 0.03 times the near-field concentration, while for more distant work (>4 m), the far-field should be 0.01 times the outdoor near-field level. Outdoor multipliers are also adjusted for dust and mists versus vapours, based on the ratio found in the indoor simulations (Table 2).

Unidirectional room airflow. Room enclosures may have special ventilation where the air is directed to flow in a single direction, referred to as enclosed booths, rooms, or cabins. The ventilation inside the room may be directed downward (downdraught or vertical airflow), cross-flow (cross-draught or horizontal airflow), or a hybrid of these two. Room enclosures can also be partially enclosed, e.g. downward laminar flow booths (or 'walk-in' booths). These booths are provided with a 'curtain' of descending laminar air between the ceiling and the rear of the booth where exhaust grilles are located at the lower section. Flow booths can be equipped with partial or full screens with glove ports, potentially offering a further level of containment (Table 2).

Due to inconclusive evidence regarding quantitative reduction in exposure that might be achieved from a unidirectional flow booth, available data were used to make the judgement that the near-field exposure levels are three times lower than without using a spray room (Andersson *et al.*, 1993; Heitbrink *et al.*, 1995). This reduction factor was derived for enclosed spray rooms provided that it conformed to certain conditions, i.e. (i) technical provisions such that it is fully enclosed, fitted with unidirectional down flow, with a volume between 30 and 1000 m^3, and with at least 10 air changes h^{-1} and (ii) proper worker behaviour, for example through training of workers with regards to the correct use and maintenance of the room. Because cross-flow spray rooms are considered to be less effective than down-flow rooms, the cross-flow spray rooms are assigned a similar multiplier as the indoor dispersion near-field multiplier.

WORKED EXAMPLE: TRANSFERRING OF POWDERED MATERIAL

To clarify the algorithm and the multipliers in the mechanistic model, we present a worked example. This worked example is derived from one of the scenarios of the pharmaceutical industry included in the calibration of ART (Schinkel *et al.*, 2011).

The operator is transferring (transfer rate = 1–10 kg min^{-1}; routine transfer; drop height <0.5 m; open process) a powdered material (fine dust; dry product; 100% active ingredient) from a container into a mixing tank, without using any localized controls. The work is performed indoors (room size equals 300 m^3) with a ventilation rate of 10 air changes h^{-1}. There are demonstrable and effective housekeeping practices in place. For the example, we assume that the worker is only conducting this one task and there is no additional far-field source in the workroom.

Table 6 shows the relevant parameters for each of the MF in the mechanistic model and the accompanying multipliers.

By using equations (1), (3) and (5), this results in a mechanistic model score of 0.024024:

$$C_{\mathrm{nf}} = \left(E_{\mathrm{nf}} \cdot H_{\mathrm{nf}} \cdot \mathrm{LC}_{\mathrm{nf1}} \cdot \mathrm{LC}_{\mathrm{nf2}}\right) \cdot D_{\mathrm{nf}},$$

$$\begin{aligned} C_{nf} = \big((0.3 \times 1.0 \times 1.0) \\ \times (1.0 \times 1.0 \times 1.0 \times 1.0) \\ \times 1.0 \times 1.0\big) \times 0.8 = 0.24, \end{aligned}$$

$$\mathrm{Su}_{\mathrm{nf}} = \mathrm{Su}_{\mathrm{factor}} \cdot \left(E_{\mathrm{nf}} \cdot H_{\mathrm{nf}} \cdot \mathrm{LC}_{\mathrm{nf1}} \cdot \mathrm{LC}_{\mathrm{nf2}} \cdot D_{\mathrm{nf}}\right),$$

$$\begin{aligned} \mathrm{Su}_{\mathrm{nf}} = 0.001 \times \big((0.3 \times 1.0 \times 1.0) \\ \times (1.0 \times 1.0 \times 1.0 \times 1.0) \\ \times 1.0 \times 1.0 \times 0.8\big) = 0.00024, \end{aligned}$$

$$\begin{aligned} C_t = \frac{1}{t_{\mathrm{total}}} \sum_{\mathrm{tasks}} \left\{t_{\mathrm{exposure}} \cdot \left(C_{\mathrm{nf}} + C_{\mathrm{ff}} + \mathrm{Su}\right)\right\} \\ + t_{\mathrm{nonexposure}} \cdot 0, \end{aligned}$$

Table 6. Application of modifying factors in the example

Modifying factor	Relevant parameter	Description	Multiplier
Substance emission potential	Dustiness	Fine dust	0.3
	Moisture contents	Dry product	1.0
	Weight fraction	100% active ingredient	1.0
Activity emission potential: (activity class: transfer of powders, granules, or pelletized material. Activity subclass: falling of powders)	Use rate	Transferring 1–10 kg min^{-1}	1.0
	Carefulness of handling	Routine transfer	1.0
	Drop height	<0.5 m	1.0
	Level of process containment	Open process	1.0
Localized controls		No localized controls	1.0
Surface contamination		Demonstrable and effective housekeeping practices	0.001
Dispersion (indoors)	Room volume	300 m^3	0.8
	Ventilation rate	10 ACH	

$$C_t = 1/480 \times (480 \times (0.24 + 0 + 0.00024) + 0 \times 0 = 0.24024.$$

This (dimensionless) mechanistic model output provides a relative score for the GM exposure of a scenario and is fitted to exposure measurements to 'translate' these scores to a quantitative exposure estimate in milligrams per cubic metre described by Schinkel *et al.* (2011). The mechanistic model output of 0.24024 in this worked example results in a 50th percentile calibrated exposure estimate of 4.9 mg m^{-3}.

CONCLUSIONS

ART is a Tier 2 exposure assessment tool combining mechanistic model estimates and exposure data. The advantage of the ART mechanistic model is that (i) it is built on the principle of a source-to-receptor conceptual model that represents the inhalation exposure process, (ii) it schematically takes account of a comprehensive list of deterministic exposure modifying factors based on (where possible) chemistry and physics laws and empirical evidence, (iii) the modifying factors associated with the substance emission and activity emission are based on systematic classification systems [in the case of the activity emission a structured taxonomy of workplace tasks or operations (referred to as activity classes) is applied]. The ART mechanistic model and its underlying principal modifying factors were extensively scrutinized in an iterative way. The expert elicitation procedure consisted of different phases (i.e. workshops, peer review) involving leading international experts from various industries, research institutes, and public authorities. The mechanistic model output provides a relative score for the GM exposure of a scenario and is fitted to exposure measurements to translate these scores to a quantitative exposure estimate in milligrams per cubic metre, as described by Schinkel *et al.* (2011).

The characterization of modifying factors summarized in this paper revealed a number of issues that need to be addressed in future research. For example, it has been shown that a 50–85% reduction of worker exposure can occur when workers are properly trained for the correct use of ventilation systems and cleaning methods and by following safe work practices (Hopkins *et al.*, 1986). However, it is very difficult to include worker behaviour in a generic exposure model, without performing detailed observations of a worker in the workplace. In the absence of sufficient evidence on the impact of worker behaviour on exposure, this component of the model has not yet been included. Because each MF will have a natural variability, in the future, one might consider using, apart from typical values for the effectiveness of controls, 'best practice' values that describe the maximum achievable effectiveness, thus representing the effectiveness with the highest degree of technology, maintenance, and training. The assigned multipliers of other MF will also have natural variability around a median value, and a future version of the mechanistic model might improve by adding distributions for multipliers for each MF instead of using typical values. In addition, other areas require further research, including the intrinsic emission potential of various solid objects, outdoor dispersion, extending the applicability domain with other types of exposure (e.g. fumes, gases, fibres, etc.), and other areas. The ART mechanistic model is an evolving system that will require updates and refinements on a continuous basis when new information will be available in the future.

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