Modeling of occupational exposure to accidentally released manufactured nanomaterials in a production facility and calculation of internal doses by inhalation

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Background: Occupational exposure to manufactured nanomaterials (MNMs) and its potential health impacts are of scientific and practical interest, as previous epidemiological studies associate exposure to nanoparticles with health effects, including increased morbidity of the respiratory and the circulatory system.

Objectives: To estimate the occupational exposure and effective internal doses in a real production facility of TiO₂ MNMs during hypothetical scenarios of accidental release.

Methods: Commercial software for geometry and mesh generation, as well as fluid flow and particle dispersion calculation, were used to estimate occupational exposure to MNMs. The results were introduced to in-house software to calculate internal doses in the human respiratory tract by inhalation.

Results: Depending on the accidental scenario, different areas of the production facility were affected by the released MNMs, with a higher dose exposure among individuals closer to the particles source.

Conclusions: Granted that the study of the accidental release of particles can only be performed by chance, this numerical approach provides valuable information regarding occupational exposure and contributes to better protection of personnel. The methodology can be used to identify occupational settings where the exposure to MNMs would be high during accidents, providing insight to health and safety officials.

Keywords: Manufactured nanomaterials, Particles dispersion, CFD modeling, Occupational exposure, Internal doses, Accidental release

Introduction

Manufactured nanomaterials (MNMs) are used in a variety of construction applications, including to enhance structural strength, promote energy conservation, and/or produce self-cleaning.^{1–3} However, in contrast to the effort devoted to the development of new MNMs with unique and favorable properties, little has been done to assess the potential health-related risks in this rapidly growing field. Researchers acknowledge that the potential occupational health and safety implications of MNMs require additional attention.^{4–7}

To characterize worker risk, the exposure to and the internal dose from MNMs need to be estimated.⁷ However, monitoring the behavior of MNMs in workplaces is often unfeasible due to economical and practical reasons.^{8,9} Computational models are an alternative to experimental

measurements for a preliminary estimation of occupational exposure and internal dose calculation.

Based on this rationale, a variety of computational models have been developed for the determination of particle dispersion in indoor environments. These studies can be categorized based on the turbulence model used for the airflow; the $k-\varepsilon$ or the RNG (re-normalization group) $k-\varepsilon$ model for the airflow turbulence,^{10–15} large eddy simulations,^{16–18} and the $k-\mu$ model.^{19,20} Models are categorized based on the description of the population of the particles to either Eulerian models (drift-flux),^{10,21–26} or Lagrangian particle tracking models.^{11,13,16–19,27} The common characteristic of most previous studies is the simulation of particle transport in simplified geometries of ventilated chambers. One exception is the work of Lai and Chen, who modeled the dispersion of particles emitted during a cooking event in a realistic representation of a kitchen and adjacent living-room, as well as the works of Lin et al. who modeled the transport of pathogens in aircraft cabins.^{28–30} However, none of these studies found a correlation

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Figure 1 Layout of the MNMs production site.

between the estimated particle concentration in space and the internal dose of people present. Alternatively, there are studies where internal dose by inhalation was calculated using numerical models, but particle exposure was measured experimentally.^{31–35} Recently, indoor aerosol modeling was used for evaluation of exposure to particulate matter, employing a semi-empirical approach to calculate the deposited dose in the respiratory tract.⁹

In the present study, computational modeling assessed occupational exposure to airborne MNMs in two stages. In the first stage, the MNMs dispersion in the space of interest and the exposure of the personnel were estimated using commercial computational fluid dynamics software. In the second stage, the doses in the different regions of the human respiratory tract (HRT) were calculated with a fully mechanistic in-house model. The proposed methodology estimated exposure and HRT doses for individuals working in an actual MNMs production facility during several scenarios of hypothetical accidental particles release.

Methods

Geometry and computational grid

The MNMs production site layout is shown in Fig. 1. Based on the provided information, the MNMs production area of the plant was recreated using ANSYS DesignModeler. Selected views of the created geometry are shown in Fig. 2. The complexity of the realistic geometry rendered the construction of a structured mesh inefficient, both in efforts and in the lack of detail. Therefore, commercial meshing software was used (ANSYS Meshing) to create the appropriate mesh. The generated computational grid is unstructured and has approximately 332 k nodes.

Air flow field simulation

Air flow field was obtained using ANSYS CFX[®] assuming isothermal flow at 25 °C and adopting the $k-\epsilon$ turbulence model. Moreover, the solution assumed a low ventilation rate of the space equal to 0.3, which translates to an inlet flow rate of $Q = 120 \text{ m}^3/\text{h}$ for the almost 400 m^3 space. This flow rate was divided into three identical air inlets of

total surface area of 0.24 m^2 located high in the rear wall of the production facility.

Dispersion of MNMs

The MNMs dispersion in the 3D space is described by the following particle transport equation (PTE):

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\vec{u}) = \nabla \cdot \left(\frac{\mu_{\text{eff}}}{\sigma_t} \nabla n \right) + S_n \quad (1)$$

where $n(\vec{r}, t)$ is the particle number concentration at point $\vec{r}$ and time t , $\vec{u}$ is the air flow velocity and S_n is the particle source. The first term in the left-hand side of Equation (1), describes the rate change of the particle number over time, whereas the second term the convective flow of particles. Moreover, the first term of the right-hand side of Equation (1) describes the Fickian diffusion of the particles, which results from the summation of the Brownian and eddy diffusion:

$$\frac{\mu_{\text{eff}}}{\sigma_t} = \mathfrak{D} + \epsilon_t \quad (2)$$

In Equation (2), μ_{eff} is the effective viscosity and σ_t the turbulent diffusivity, whereas ϵ_t is the eddy/turbulent viscosity and $\mathfrak{D}$ the Stokes-Einstein diffusion coefficient defined as:³⁶

$$\mathfrak{D} = \frac{k_B T_{\text{air}} C_c}{3\pi \mu_{\text{air}} d_p} \quad (3)$$

where k_B the Boltzmann's constant, T_{air} and μ_{air} the temperature and dynamic viscosity of air, d_p the particle diameter and C_c the Cunningham slip correction factor.

It should be noted that the PTE written in Equation (1) was used only for the description of indoor particle dispersion of interest. Moreover, Equation (1) does not include particle transformation processes. Nonetheless, previous studies demonstrate that given sufficient time, released ultrafine particles will aggregate during dispersion, likely significantly altering personnel exposure.^{37,38} Due to a lack of information regarding the aggregation parameters in the specific facility and the small duration of the simulation, MNMs aggregation was neglected and the population of the particles was considered monodispersed throughout the present study. The PTE (Equation (1)) was solved numerically using ANSYS CFX[®].

Lung transport and deposition model

Particle transport and deposition within the regions of the HRT were determined using a numerical model that describes aerosol dynamics based on an Eulerian approach. The model predicts the temporal variation of the number concentration and the regional deposition of the inhaled particles during a breathing cycle by solving the aerosol general dynamic equation considered in a one-dimension form along the flow direction:

Figure 2 Views of the computationally reconstructed realistic geometry; MNMs production site and locations of the hypothetical accidental release scenarios (top).

$$\frac{\partial}{\partial t}(A_i n_i) = -\frac{\partial}{\partial x}(A_i u n_i) + \frac{\partial}{\partial x}\left(A_i \mathfrak{D}_i \frac{\partial n_i}{\partial x}\right) - V_{d_i} \Gamma n_i + \left[\frac{\partial}{\partial t}(A_i n_i)\right]_{\text{growth}} + \left[\frac{\partial}{\partial t}(A_i n_i)\right]_{\text{coag}} \quad (4)$$

where n_i the particle number concentration in section i of the size distribution, u the air velocity, $\mathfrak{D}_i$ the diffusion coefficient of particles with size i , A_i and A_A the time dependent and constant cross-section of all airducts, respectively, at distance x from the respiratory system entrance, Γ the circumference of air ducts and V_{d_i} the particle deposition velocity. In brief, the equation states that the rate of change of the particle number concentration over time (left-hand side of Equation (4)) is a result of several processes acting simultaneously on the inhaled particulate matter. These processes are described on the right-hand side of Equation (4) and are convection (1st term), axial diffusion (2nd term), deposition (3rd term), condensational growth (4th term) and coagulation/aggregation (5th term), respectively. The description of the above mechanisms is based on standard theory for the respective aerosol processes, avoiding the use of empirical correlations.

The respiratory tract consists of the thoracic (lung) and the extrathoracic regions. The thoracic region of the respiratory tract is described with the help of the classical morphometric model “A” by Weibel.³⁹ The volume of the alveolated section of the lung was allowed to vary with time to accommodate breathing dynamics effects. A simplified morphological scheme consisting of sequential cylindrical airways describes the extrathoracic region through the mouth pathway. The air velocity along the airways of the respiratory tract was determined by solving the equation of continuity.

The aerosol deposition was studied for the extrathoracic part of the respiratory tract and the two main regions (tracheobronchial, TB, and alveolar-interstitial, AI) of the thoracic part. In the tracheobronchial region the deposition was enhanced with increasing particle diameter, due to the mechanism of inertial impaction. On the other hand, the deposition in the alveolar part was reduced for coarse particles. The main deposition mechanism in the specific part of the lung is the Brownian diffusion that enforces the deposition of fine particles. The deposition along the extrathoracic (ET) region was determined by

Figure 3 Views of air flow field around the MNMs production machine (streamlines and velocity magnitude contours); (a) yz-plane, (b) zx-plane, and (c) xy-plane.

the mechanism of inertial impaction that affects primarily coarse particles.

The number concentration of each particle size is functions of time along the whole respiratory tract in one dimension, i.e. $n_i = n_i(x, t)$ was determined through the solution of Equation (4). The particles deposition fraction (DF) in a specific part of the lung with length L , e.g. a lung generation, is the fraction of the number of particles that deposit in this part divided by the number of particles that enter the respiratory tract during a breathing cycle of period. T^{38}

$$DF = \frac{\sum_{i=1}^{n_B} \int_0^T \int_0^L n_i V_{d_i} \Gamma \, dx \, dt}{\sum_{i=1}^{n_B} \int_0^T \int_0^L n_{i0} A_{A0} u_0 \, dt} \quad (5)$$

where A_{A0} and u_0 are the cross-sectional area and the air velocity, respectively, at the entrance.

The model was validated against a large body of experimental and numerical respiratory data, for both inert and hygroscopic aerosols, and the predictions of the empirical model employed by the International Commission on Radiological Protection (ICRP).³⁹ A detailed description of the model, its validation and application potential were previously published.^{40–42}

Results and discussion

Air flow field

The obtained flow field was complex as a result of the different parts of the MNMs production machine that stand in the space and are located in front of the air inlets of the ventilation system. However, the air velocity was low

throughout the facility due to the low air exchange rate. In Fig. 3, the different two-dimensional views (i.e. planes) of the facility show the zones of intense recirculation of air (streamlines) around the production machine and the air velocity magnitude (contour) in these planes.

Particles dispersion

In the present study, we examined particle dispersion in an MNMs production facility during a hypothetical accidental release of TiO_2 MNMs. We identified some parts of the production machine where a malfunction could lead to the escape of the manufactured particles into the surrounding space. Table 1 describes the different accidental release scenarios as well as the estimation of the MNMs release and the actual emission for each scenario. The emissions are based on an estimated MNMs production rate of 250 g/h. In all scenarios, narrow particle size distributions can be assumed, i.e. monodispersed particle populations, although not all scenarios have the same particles dimension; for scenarios A, B, C, E, and G the particle diameter is equal to $d_p = 20\text{nm}$, ($20 \times 10^{-9}\text{m}$) (i.e. the nominal diameter of the produced MNMs), whereas for scenarios D and F the particle diameter is $d_p = 1\text{ }\mu\text{m}$, ($1 \times 10^{-6}\text{m}$), because it is thought that in these locations the MNMs have already aggregated considerably. In Fig. 2 (top), the different accidental release scenarios are related to the different parts of the production machine.

Equation (1), was solved numerically assuming an initial background concentration of MNMs equal to zero and taking into account the air flow field in the production site, as calculated earlier. The total simulation time for

Table 1 Hypothetical accidental scenarios for the MNMs production facility.

Scenario	Issue	Released MNMs (%)	Emissions (g/h)
A	Failure at the joint of the burner door	30	75
B	Failure at the joints of the external case of the burner	15	37.5
C	Failure at the sampler connections	10	25
D	Failure at the hermetic sealing of the collection hopper valve	25	62.5
E	Inlet filter break due to wear	5	12.5
F	Failure at the chimney HEPA filter box	5	12.5
G	Accidental drilling of the piping	5	12.5

each case was 30 min (1800 s). This time frame was considered appropriate for the particular space and working conditions as it gives enough time for the personnel to evacuate (none of the proposed scenarios were violent enough to cause injury).

In addition, it was assumed that the particles escaped the machine from surface sources of arbitrary shape, but in all cases the source had a surface area of around 100 cm². The release of MNMs, R [#m³], follows an exponential pattern:

$$R = n_{\text{final}}[1 - \exp(-t/t_c)] \quad (6)$$

where n_{final} [#m³] is the final (maximum) MNMs mass concentration calculated by dividing each scenario emission (fourth column of Table 1) by a production machine ventilation flow equal to 1600 m³/h. In Equation (6), t_c [s] is the time constant of the exponential function. It was assumed that the maximum concentration was reached fairly quickly, thus the time constant was set to 5 s. Therefore, the maximum release happened 30 s after the beginning of the accident.

The assumptions for the surface area of the source and the exponential pattern of release were based on discussions with facility personnel. In particular, it was thought that none of the hypothetical accidents presented here could be related to a violent event (e.g. an explosion), but rather were limited material failure in specific parts of the production machine. Moreover, it was our intention to use the same surface area for all sources and this area would be a small portion of the corresponding part of the machine, irrespective of their location on the machine. The chosen surface area of around 100 cm² satisfies the aforementioned criteria. Furthermore, it was suggested that in case of such non-violent accidents a fairly steady rate of escaping particles should be expected. Thus, an exponential pattern with small time constant seemed adequate to describe the MNMs release from the source.

In Figures S1–S7 of the Supplementary Material, snapshots of the calculated MNMs dispersion are shown for all accidental release scenarios through the isosurface of particle number concentration of 10⁹ #/m³ for the ones that correspond to 20 nm articles (A, B, C, E, and G) and of 10⁶ #/m³ for the ones that correspond to 1 µm articles (D and

F). As shown in a preliminary study with simplified geometry (not presented here) and in accordance with findings of others,²¹ the dispersion of particles in the production site is governed mainly by diffusion, thus initially the particles form a somehow spherical isosurface around the source. Later, as particles start to get carried away by the ventilation air flow, the isosurface resumes more irregular shapes. These figures also show which areas of the MNMs production site were most affected (or contaminated) in each accidental scenario. For example, the area on the platform was most affected in scenario A (Sup. Material 1 Figure S1), whereas the area behind the production machine was more affected in scenario D (Sup. Material 1 Figure S4).

In Figure S8 of the Supplementary Material, the isosurface of the 0.1 mg/m³ is shown for all accidents at 30 min after the accidents start. In all examined cases, the areas where the particle (mass) concentration reaches the 0.1 mg/m³ limit were confined near the source of the particles on the production machine. The calculation of the MNMs mass concentration from the number concentration obtained by the model was based on the assumption that the TiO₂ particles are spherical. The change of metrics was based on the fact that the available proposed occupational exposure limits (OEL) are in mass concentration. In particular, for TiO₂ particles SCAFFOLD Project^{43,44} suggests an OEL equal to 0.1 mg/m³ for an 8 h working shift, whereas NIOSH⁴⁵ an OEL equal to 0.3 mg/m³ for a 10 h working shift.

Exposure estimation

Obtaining the MNMs dispersion in the production site as shown, it was possible to predict the exposure of persons working in different areas of the production site during these accidental releases. Assuming that the person's height was 1.75 m, his/her breathing zone was approximately 1.65 m from the floor. The exposure to MNMs was monitored for the five monitoring points (MPs) shown in Fig. 4 along with the MNMs sources for each accidental scenario. Monitoring point MP1 corresponds to someone standing on the platform by the production machine, MP2 to someone standing near the MNMs storing boxes, MP3 to someone seating in front of the production machine (below the platform, in this case the MP is at is at around

Figure 4 Occupational exposure monitoring points (MP).

1.25 m from the floor), MP4 to someone standing by the MNMs packaging table, and MP5 to someone standing near the MNMs collection hopper.

In Fig. 5, the calculated exposure at the different MPs is shown indicatively for accidental release scenarios A (top) and D (bottom). In all cases, MNMs concentration at the MPs increased gradually by several orders of magnitude (notice the logarithmic scale of the y-axis in the diagrams). As expected, the exposure was higher at the working stations (MPs) closer to the MNMs source. For example, for accidental scenario A the exposure was higher for someone standing on the platform (MP1), whereas for accidental scenario D someone standing by the collection hopper (MP5) got the higher exposure.

Based on the 30 min exposure diagrams (Fig. 5), the time average exposure at the different MPs was calculated for all accidental release scenarios. The average exposure is shown in Table 2 for all accidental release scenarios that

Figure 5 Occupational exposure at the different MPs over time for accidental release scenarios A (top) and D (bottom).

Table 2 Time average exposure to MNMs for all MPs and accidental scenarios.

Scenario	Time average exposure (#/m ³)				
	MP1	MP2	MP3	MP4	MP5
A	6.28E+10	3.56E+07	4.00E+09	4.01E+07	2.40E+08
B	3.08E+10	5.56E+07	3.64E+09	2.39E+07	1.36E+08
C	5.78E+08	1.02E+07	4.26E+08	3.61E+06	3.37E+08
D	1.60E+02	1.24E+00	7.17E+02	8.13E+04	4.76E+07
E	1.93E+07	1.27E+05	9.45E+05	3.81E+10	6.92E+09
F	9.95E+02	2.61E+04	5.13E+01	5.52E+02	4.25E+00
G	1.32E+09	6.01E+06	7.23E+08	1.54E+06	4.76E+06

Figure 6 Deposition fraction, DF, in the different regions of the HRT for 20 nm and 1 µm MNMs.

involve MNMs of 20 nm size (that is scenarios A, B, C, E, and G), the ones that involve 1 µm MNMs (scenarios D and F). From this table, it is easy to recognize the working stations (or MPs) most affected in each accidental release scenario; the closer the MP was to the site of the accident, the higher the exposure. If one converts the proposed OEL (by SCAFFOLD Project⁴³) to number of particles per m³ of air, then this reads 6×10^{12} for the 20 nm particles and 5×10^7 or the 1 µm particles. It is clear from Table 2 that none of the simulated hypothetical accidental release scenarios resulted in an exposure higher than the OEL.

HRT dose calculation

The time average exposures (Table 2) were used in the HRT particle transport and deposition model to estimate the particle dose in the different regions of the respiratory tract. In all cases, results were obtained assuming that the person working at the different MPs is a Caucasian man or woman (age 30 y, height 1.76 m and weight 73 kg), and that the job undertaken corresponds to light exercise. The reference respiratory values for the physiological parameters are the ones proposed by ICRP³⁹ for personnel; functional residual capacity 3.3×10^{-3} m³, tidal volume (V_T) 1.25×10^{-3} m³, and respiration frequency (f_R) 20 min^{-1} .

The particles DF, in the HRT depends on the particles diameter and density and the person's physiology and activity level. The calculations of the DF for the two different TiO₂ MNMs diameters involved in the accidental release scenarios (20 nm and 1 µm) were calculated. In total, 85% of the 3.3×10^{-3} m³ and 91% of the 1 µm MNMs

Figure 7 Total number of deposited particles in the whole HRT after 30 min exposure for the 20 nm accidental release scenarios.

Figure 8 Total number of deposited particles in the whole HRT after 30 min exposure for the 1 µm accidental release scenarios.

were deposited in the HRT (Fig. 6). However, the bigger particles typically deposited in the extrathoracic (ET) region of the respiratory tract, whereas the 20 nm MNMs penetrated the first generations of the lung and deposited mainly in the alveolar-interstitial region. In fact, for the 20 nm articles, alveolar-interstitial deposition constituted almost 71% of the total deposition, in contrast to the 16.5% that deposit in the tracheobronchial region and the 12.6% that don't pass through the extrathoracic part of the HRT. The opposite holds for the 1 µm particles; extrathoracic deposition constitutes 73.4% of the total deposition.

The total number of deposited particles (or dose) in each HRT region, D_j , for the whole 30 min of exposure, was calculated by the formula:

$$D_j = N_{d,j} \times 600 \quad (7)$$

where $N_{d,j}$ is the absolute number of deposited particles per breath in the j -th region of the HRT and 600 is the number of breaths taken in 30 min (i.e. 1800 s/3 s). In Equation (7), j can be TOTAL if it refers to the dose in the whole HRT or ET, TB, AI if it refers to the extrathoracic, tracheobronchial or alveolar-interstitial region of the HRT, respectively.

In Figs. 7 and 8 the total number of the deposited particles is given for the different accidental release scenarios per MP for the scenarios that involve 20 nm and 1 μ m particles, respectively. We found that the doses were higher in the MPs closer to the MNMs source for each accidental release scenario, as expected by the higher exposure in the same MPs (Table 2).

In Table S1 of Supplementary Material 2, the particles dose in the respiratory tract as a total, as well as in the HRT regions is given for all accidental release scenarios and MPs, both in number and mass. This table also demonstrates the effect of the metrics on the estimation of the dose. For example, when the dose in number (D [#] labeled columns) was considered, it was evident that the accidental release scenarios that involved 20 nm MNMs resulted in higher doses in most MPs than scenarios D and F that involved 1 μ m MNMs. However, based on mass it was clear that when 1 μ m MNMs were involved the (mass) doses were almost in every MP higher than the doses related to the 20 nm cases.

Conclusions

In this study, we numerically assessed occupational exposure and internal doses to airborne MNMs. The approach consisted of two parts. The first part had three steps: (a) the representation of the space of interest and the creation of the computational grid, (b) the calculation of the airflow in this space, and (c) the calculation of MNMs dispersion in this space over time. In the second part, the particles dose in the different regions of the respiratory tract was estimated numerically following the occupational exposure as found in the first part. In-house and/or commercial software was used for each step of the study.

The developed methodology was used initially to calculate particle dispersion in a real production site of TiO₂ MNMs during hypothetical accidental release. In addition, the occupational exposure during these accidents was estimated. The geometry of the MNMs production facility was computationally represented. Due to the complexity of the space we chose to create an unstructured computational grid using commercial software. As expected, the solution for the airflow field showed that complexity of the geometry results to a complex velocity field. However, the low air exchange rate also resulted in low velocities

throughout the space. The obtained air velocity field was used to numerically obtain particles dispersion. The simulations were based on expected emissions for each accidental release scenario, and in each run we simulated 30 min of continuous particle release from the damaged area on the production machine. The results showed that depending on the scenario, different areas of the production site were affected by the released MNMs. Moreover, the exposure at the breathing zone of people working in different areas of the production site was monitored; the particle mass concentration over the 30 min period was obtained, and the time average exposure was calculated. In all studied accidental release scenarios the concentration at the breathing zone of the personnel was below the selected OEL of 0.1 mg/m³ for TiO₂ particles.

The averaged exposure values served as input to the HRT particles transport and deposition model (second part) to estimate doses in the respiratory tract of people in different places in the production site during the hypothetical accidents. In particular, the particles DF for 20 nm and 1 μ m MNMs was estimated and it was demonstrated that the smaller the particles, the deeper they penetrate in the lungs generations, as anticipated. Moreover, the total dose for 30 min exposure to the accidentally released MNMs was calculated in both total number and total mass of deposited particles for all accidental release scenarios. As expected, the HRT dose is higher for the persons closer to the particles source in all cases. The different dose metrics demonstrated that the smaller particles give in general higher number doses, than bigger particles, but the opposite holds for the mass-based doses.

Overall, the study may be further improved by validating with experimental data the methodology related to the indoor dispersion of the released MNMs and also include the effect of transformation processes in the simulations. In this case, experimental data relevant to the studied facility were not available, which is the reason we chose to use commercial software widely applied in these kinds of studies instead of in-house computational fluid-particle dynamics codes. It is important to point out that the in-house software Mitsakou et al.⁴⁰ used for the calculation of MNMs doses in the respiratory tract is well-validated against experimental findings, data from other numerical models, and the results of empirical models.

The applicability of the methodology is not limited to this specific scenario. The software used in each step of the methodology, either commercial or in-house, is based on a mechanistic description of the phenomena involved and therefore can be adapted for multiparametric studies. Our fully numerical approach allows for the calculation of MNMs release and dispersion, occupational exposure and doses in the various parts of the HRT as functions of the space, ventilation and particles features as well as the individual's physiological and physical characteristics. It is the author's opinion that such a multiparametric numerical tool can provide valuable information regarding the

occupational exposure and serve as a support decision tool regarding the safety of the personnel during accidental MNMs release.

Supplementary material

The supplementary material for this paper is available online at <http://dx.doi.org/10.1080/10773525.2016.1226535>.

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