Journal of Environmental Radioactivity 127 (2014) 119–126

Contents lists available at ScienceDirect

Journal of Environmental Radioactivity

journal homepage: www.elsevier.com/locate/jenvrad

The influence of human physical activity and contaminated clothing type on particle resuspension

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ARTICLE INFO

Article history:
Received 12 July 2013
Received in revised form
11 October 2013
Accepted 17 October 2013
Available online 5 November 2013

Keywords:
Resuspension
Human physical activity
Clothing
Hazardous aerosol particles
Contamination
Shedding

ABSTRACT

A study was conducted to experimentally quantify the influence of three variables on the level of resuspension of hazardous aerosol particles from clothing. Variables investigated include physical activity level (two levels, low and high), surface type (four different clothing material types), and time i.e. the rate at which particles resuspend. A mixture of three monodisperse tracer-labelled powders, with median diameters of 3, 5, and 10 microns, was used to "contaminate" the samples, and the resuspended particles were analysed in real-time using an Aerodynamic Particle Sizer (APS), and also by Neutron Activation Analysis (NAA).

The overall finding was that physical activity resulted in up to 67% of the contamination deposited on clothing being resuspended back into the air. A detailed examination of the influence of physical activity level on resuspension, from NAA, revealed that the average resuspended fraction (RF) of particles at low physical activity was 28 ± 8%, and at high physical activity was 30 ± 7%, while the APS data revealed a tenfold increase in the cumulative mass of airborne particles during high physical activity in comparison to that during low physical activity. The results also suggest that it is not the contaminated clothing's fibre type which influences particle resuspension, but the material's weave pattern (and hence the material's surface texture). Investigation of the time variation in resuspended particle concentrations indicated that the data were separable into two distinct regimes: the first (occurring within the first 1.5 min) having a high, positive rate of change of airborne particle concentration relative to the second regime. The second regime revealed a slower rate of change of particle concentration and remained relatively unchanged for the remainder of each resuspension event.

1. Introduction

Following an accidental or deliberate release of hazardous materials, such as radioactive (e.g. Fukushima) or infectious species (e.g. H1N1 virus) to the atmosphere, there is a risk of exposure of large population groups and individual persons who reside both indoors and outdoors. In preparing for this scenario, accurate estimates of whole body exposure arising from all exposure pathways are necessary in order to design effective countermeasures. Current dosimetric models, for example, that of Andersson et al. (2004), focus on aerosol inhaled while initially airborne, with some reference to particles deposited on the human body, but secondary exposure and inhalation is not considered. One secondary exposure pathway that merits investigation, and for which no comprehensive experimental data are available, is re-exposure to aerosol contaminant that was formerly deposited on clothing and other indoor surfaces. This is especially important in the case where a person might be unwittingly contaminated and might spread this contamination to others via the process of resuspension. These exposure pathways may also have significance for airborne pollutants that are nonradioactive, e.g. infectious aerosol that becomes re-entrained from disturbance of hospital bedding, etc.

Numerically, resuspension rates are low relative to deposition rates (e.g. Thatcher and Layton, 1995) but the concentration of resuspended contaminated particles can significantly influence a persons' exposure. The size distribution of resuspended particles is different from the size distribution of depositing particles, with larger particles being more readily resuspended (Andersson et al., 2004; Ferro et al., 2004).

A wide range of *contaminated surfaces* have been investigated in the context of particle resuspension due to human physical activity,

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http://dx.doi.org/10.1016/j.jenvrad.2013.10.012

but resuspension studies focus on quantifying the level of resuspension from flooring surfaces (Ferro et al., 2004; Long et al., 2000; Abt et al., 2000); contamination on, and its removal from, clothing surfaces has received little attention, apart from a few studies in the medical devices and cleanroom industry (Cohen and Positano, 1986; Bohne and Cohen, 1985). The removal of particles from human skin has been investigated; Hession et al. (2006) studied the effect of human body hair on particle fall-off and concluded that hairy skin retained particles for longer periods. To supplement the existing knowledge base, the aim of the present study is to quantify the level of resuspension of hazardous particles directly from clothing surfaces worn by a physically active human, who is engaging in various levels of typical daily physical activity. Earlier studies have generally determined particle resuspension rates and factors based on changes in the total airborne particulate concentrations, which is not chemically specific and so could not directly isolate the resuspended particles from others that were airborne. While the current study also uses this accepted experimental method, an additional and more comprehensive method, using Neutron Activation Analysis (NAA), will be used to calculate the fraction of originally deposited particles which resuspended, directly from the clothing surface.

2. Materials and methods

A summary of the experimental strategy for studying particle resuspension from clothing surfaces is as follows: the material surfaces to be 'contaminated' were first exposed to aerosol particles in the form of tracer labelled silica powder. They were subsequently attached to a volunteer who engaged in a predefined physical activity for a specified length of time. Samples of the material were analysed both before and after the resuspension process to determine the proportion of the original deposited mass which became resuspended. The air in the resuspension chamber was continuously monitored to determine the size spectrum of resuspended particles in the air.

2.1. Aerosol particles

The particles used throughout these experiments were monodisperse silica particles (Alltech) labelled with a rare earth metal tracer. Three particle sizes, with manufacturer specified mean diameters of 3 μm, 5 μm and 10 μm, were chosen for their similarity to that of the refractory group of radioactive aerosols released into the atmosphere following a nuclear explosion and also to that of some biological species e.g. anthrax. It is important to note that although the particles were monodisperse, each batch of particles will have a size distribution about their mean diameter. The three sizes were labelled with Europium ($EuCl_3$), Dysprosium ($DyCl_3$) and Indium ($InCl_3$) respectively following the method described by Jayasekera et al. (1989). For Dysprosium, the average labelling yield was 5.20 mg of Dy on 1 g of labelled silica. To reduce the number of experimental replications that needed to be carried out and also the cost of analysis, the three particle sizes were mixed together for deposition onto the surfaces for all experiments.

2.2. Aerosol deposition

All clothing samples to be used in the resuspension experiments were first contaminated with the silica particles in a 2.25 m^3 aluminium deposition chamber. Inside the chamber a small 2W fan was mounted 0.2 m from the chamber ceiling (chamber height = 1.5 m), centrally aligned and orientated vertically downwards, to simulate real room mixing conditions. An Aerodynamic Particle Sizer (APS) was operational during the deposition events.

The particles were injected into the chamber using a dry powder particle generator (Palas RBG-1000) located on the roof of the chamber. In all cases, the aerosol was passed through a tube containing an array of 12 × 33 KBq Am241 radioactive sources; using the calculations of Cooper and Reist (1973) it was estimated that, for the aerosol flow rate used, the ratio of the residence time of the aerosol in the tube and the characteristic source strength used was greater than unity, so that aerosol charge equilibrium would be reached.

Before commencing the 'contamination' of fabric samples, the floor of the deposition chamber was analysed for any variations in the spatial uniformity of particle deposition; a variation of only 9% was observed over a central floor area of 43 × 76 cm.

2.3. Clothing surfaces

As the human body is typically covered with some degree of clothing, four common clothing materials were chosen for the experiments: cotton, polyester, fleece and denim. The chosen materials consisted of natural and synthetic fibres with smooth and rough surface textures. The natural fibre used was a 100% cotton material. It had the same tight weave pattern as the 100% polyester material which is a synthetic fibre, as observed by electron microscopy. Fleece is also made from 100% polyester but has a much rougher surface texture resulting from the disordered nature of the weave. A denim material was chosen due to its popularity as a clothing textile and the particular denim used in this work consisted of 65% cotton, 32% polyester and 3% spandex. As these materials were composed of different fibres and colours, they were pre-tested by Neutron Activation Analysis (NAA) to ensure they did not contain elements that would interfere with the analysis of the tracer particles to be deposited onto them.

Large samples of each material type were contaminated for each experimental run. This was to ensure there would be a sufficient level of contaminant available on the volunteer during the resuspension process, to be resuspended and thus captured by the

Fig. 1. Specific locations of contaminated samples on volunteer.