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Article:
McDonagh, A and Byrne, MA (2014) The influence of human physical activity and contaminated clothing type on particle resuspension. Journal of Environmental Radioactivity, 127. 119 - 126. ISSN: 0265-931X

https://doi.org/10.1016/j.jenvrad.2013.10.012

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The Influence of Human Physical Activity and Contaminated Clothing Type on Particle Resuspension

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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 minutes) 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.

Keywords

Resuspension; Human physical activity; Clothing; Hazardous aerosol particles;

Contamination; Shedding.

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, 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 Positao, 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, 5µm 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 x 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 x 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.

Figure 1. Specific locations of contaminated samples on volunteer

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 aerosol sampling equipment. Contaminated material samples were placed onto the volunteers' legs, arms and chest, as can be seen in figure 1. The leg pieces were 25 x 40 cm and were wrapped around each lower leg, thus covering almost all of the lower legs (front and back) between the knee and ankle. The chest piece was 20 x 20 cm and the arm pieces were 15 x 30 cm, one each on the outer arm between the shoulder and elbow. The clothing samples had safety pins attached to their corners before contamination. This was to facilitate quick and easy attachment of the contaminated samples to the volunteer (by an assistant), with a minimum of disturbance to the samples themselves. Each of the large clothing samples also had two smaller pieces of the same material (ranging from 1 x 4 cm to 2 x 5 cm, depending on the material type) pinned onto them before contamination. These were both analysed by NAA, one before and one after the resuspension process, for reasons which will be discussed in section 2.5. The size of the NAA capsules restricted the

size of material sample which could be analysed.

2.4 Aerosol Resuspension

After contamination, the clothing samples were placed into individual, sealed and labelled plastic containers and transported to the vicinity of the resuspension chamber, a purpose-built 15 m^3 plywood test room. Inside the chamber were two APS's, one at ankle height (15 cm from the floor) and the other at waist height (90 cm from the floor). In the centre of the chamber floor was a grounded metal plate upon which the volunteer stood while performing the experiment. This was to ensure that any static charge generated by the movement of the volunteers' feet, would not influence the behaviour of the resuspended particles. Also, the smooth surface texture of the metal made it easier to ensure complete decontamination between experiments.

Directly outside the chamber, the volunteer dressed in a clean room suit (Macrobond hooded coverall from Caulfield Industrial), booties (Polylatex shoecover 4 g from Caulfield Industrial), gloves (powder free purple nitrile) and a mask (8835 FFP3D disposable mask from Anderco Safety). The cleanroom suit was chosen for its nonlinting and anti-static properties, so that it can be assumed that any airborne particles detected by the APS's were as a result of particles resuspending from the contaminated material and not from the volunteer's personal clothing. An assistant then carefully removed one of the four types of 'contaminated' clothing samples from their boxes and pinned them to the volunteer's clean room suit. The placing of clothing samples over the clean room suit will generate an effect similar to that of a person wearing multiple layers of clothing (denim jeans over underwear, jumper over t-shirt etc.).

When fully attired and with samples attached, the volunteer entered the resuspension chamber and participated in one of two pre-defined physical activity patterns: low physical activity – walking at a pre-defined rate for 20 minutes, or high physical activity – Irish dancing to a Reel (Wikipedia, accessed Nov 2011) with added swinging of the arms for 10 minutes (chosen to facilitate the accurate reproduction of movement in each repeated experiment). The duration of the resuspension event for high physical activity was half that for low physical activity as the level of physical exertion required was not possible to keep constant over a longer period of time. The volunteer then exited the chamber and the assistant removed the clothing samples and placed them back into their individual boxes. The resuspension chamber and all equipment were thoroughly cleaned between experiments by washing with water and using alcohol wipes. Additionally, a multi-functional air purifier (model XJ-3000C by Heaven Fresh) with a HEPA filter, carbon filter, ioniser and sanitiser was operational between experiments, to ensure the air was completely devoid of any tracer particles.

2.5 Analysis

The primary aerosol measuring instrument used in this study was the Aerodynamic Particle Sizer (APS) [Model 3321 by Trust Science Innovation (TSI)]. The APS sizes airborne particles in the range of 0.5 to 20 µm in aerodynamic diameter. Throughout these experiments, the concentration and size distribution of the airborne particles in both the deposition and resuspension chambers were continuously measured in real time using the APS's. The second analysis technique employed was Neutron Activation Analysis (NAA). The surfaces contaminated with labelled silica were analysed by NAA at the Reactor Institute in the Delft University of Technology, the Netherlands. NAA allows discrete sampling of elements as it disregards the chemical form of a sample, and focuses solely on its nucleus.

The three rare earth metal labels used in these experiments have a half-life of 9.3 h, 2.3 h and 54 min for Eu, In and Dy respectively and they decay as follows: ^{151}Eu (+ neutron) = ^{152m}Eu (- γ) = ^{152}Gd, ^{164}Dy (+ neutron) = ^{165}Dy (- γ) = ^{165}Ho, ^{115}In (+ neutron) = ^{116m}In (- γ) = ^{116}Sn. The third analysis technique used was Scanning Electron Microscopy (SEM).

3. Results and Discussion

3.1 Airborne mass concentration variation with time, during resuspension

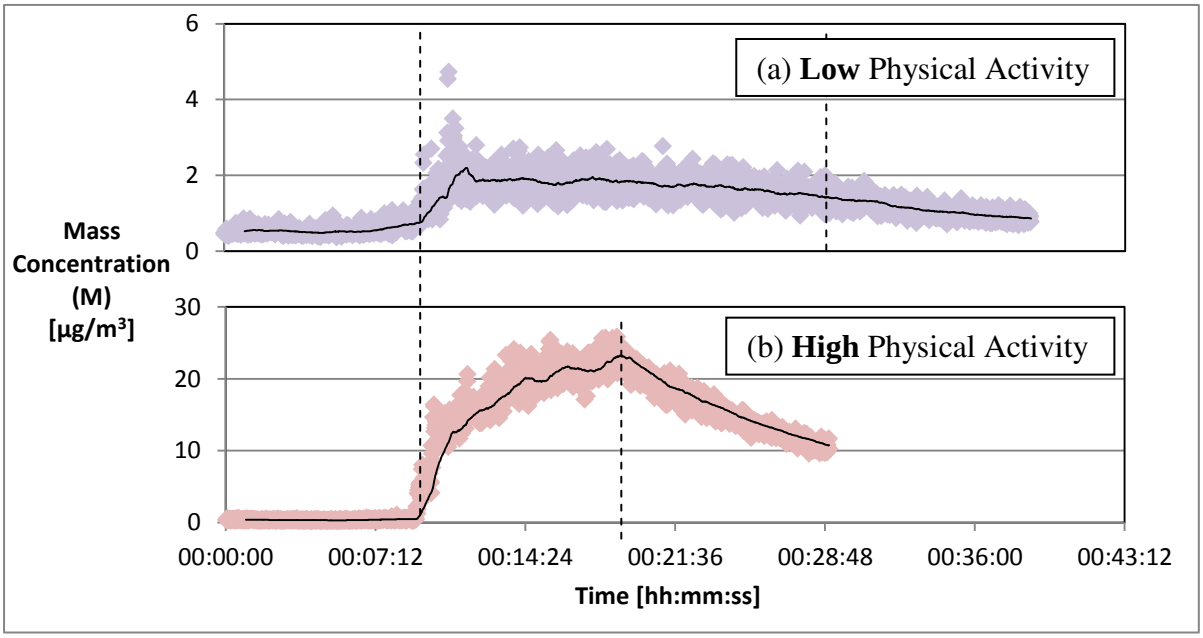

Figure 2. Mass concentration of airborne particles during resuspension due to (a) low physical activity and (b) high physical activity, as a function of time

Figure 2 indicates the change in particle mass concentration with time (as detected by an APS in the resuspension chamber) before, during and after a person wearing contaminated

clothing is engaging in (a) low physical activity and (b) high physical activity. Each data point represents the cumulative sum of the airborne mass concentration over all particle sizes, at a particular second and the trendline indicates the one minute average. The vertical dashed lines indicate the instances when the contaminated person entered and exited the resuspension chamber i.e. the start and end of the resuspension event. During low physical activity, the contaminated person was physically active within the resuspension chamber for 20 minutes and for 10 minutes during high physical activity.

It is clear from figure 2(a), that there is an immediate and steady increase in airborne particle concentration from the moment the person enters the chamber. The averaged cumulative concentration reaches a peak of 2.26 $\mu g\ m^{-3}$ just 1.5 minutes after the resuspension event begins. The particle concentration then rapidly decreases to 1.81 $\mu g\ m^{-3}$ in a further 30 seconds. After that point (2 minutes into the resuspension event) the airborne particle concentration slowly decreases. A linear trendline (best fit to data) plotted to the airborne particle concentration readings for the last 18 minutes of the resuspension event indicates a decreasing slope: i.e. a decrease in the rate of change in airborne particle concentration of $-0.026 \pm 0.002\ \mu g\ m^{-3}\ min^{-1}$.

The pattern shown in figure 2(b) is similar to figure 2(a): there is an immediate and steady increase in airborne particle concentration from the moment the person enters the chamber. However, the difference in pattern for figure 2(b) is that the airborne particle concentration now continually increases throughout the entire 10 minutes of the resuspension event. The peak averaged concentration of approximately 23.2 $\mu g\ m^{-3}$ occurs at the end of the resuspension event, just as the contaminated volunteer exits the chamber.

The rate of change of airborne particle concentration during resuspension for both physical activity levels can be split into two separate regimes, the first occurring during the initial 1.5

minutes, and the second over the remainder of the resuspension event. For the first regime - during the first 1.5 minutes of the resuspension event - both physical activity levels result in an increase in airborne particle concentration but high physical activity results in a rate of increase four times that corresponding to low physical activity, i.e. 4.5 ± 0.5 µg m^{-3} min^{-1} and 1.1 ± 0.2 µg m^{-3} min^{-1}, respectively.

For the second regime – during the remaining period of each resuspension event – the change in airborne particle concentration shows an opposing trend for low compared to high physical activity levels. During low physical activity, the particle concentration decreases at a comparatively slow rate of - 0.026 ± 0.002 µg m^{-3} min^{-1}, while it increases and at a more rapid rate of 1.00 ± 0.03 µg m^{-3} min^{-1} during high physical activity.

Wu et al. (1992) noted a very similar pattern in resuspension with time when examining the resuspension of uranine particles, polymer microspheres, lycopodium spores and Johnson grass pollen from glass, plexiglass and white oak leaves at windspeeds of 4 to 8 ms^{-1}. They concluded that the resuspension rates varied over time, defined by two separate regimes. The first regime occurred in the first minute of resuspension and was characterised by higher resuspension rates (0.17 s^{-1}). After the first minute, particles which are easily resuspended had been removed, leaving only particles with much smaller resuspension rates (0.029 s^{-1}) for the second regime. The noting of two resuspension regimes is identical to this current study and also the time frame for the first regime is similar, with Wu et al. (1992) noting 1 minute and this study observing 1.5 minutes. However the slower resuspension rate during the second regime as determined by Wu et al. (1992) is comparable only to the decrease in the rate of change of airborne particle concentration detected in this study at low physical activity. High physical activity resulted in an increase in the rate of change of airborne concentration during the duration of the second regime (albeit at a slower rate in comparison to the first regime).

Hession et al. (2006) compared the clearance of fluorescent 3 and 10 µm particles from skin during two different activity levels: low activity where the volunteer remained seated indoors, and high activity where the volunteer engaged in vigorous outdoor walking in dry, breezy conditions. The rates of clearance of particles from the skin with time during low activity was shown to follow an exponential pattern, however a very different clearance pattern was displayed during high activity. Based on figure 3.3 in Hession et al. (2006), during high activity, the mass of particles remaining on the volunteer's skin reduced by approximately 88 % in the first 30 minutes and then remained approximately constant for the remaining 170 minutes. This again displays a two regime removal of particles from a surface with time and also exhibits a difference in the particle clearance pattern between two different physical activity levels. This will be elaborated upon in the section 3.2.

3.2 Resuspension with varied physical activity level

The purpose of this section is to examine the resuspended fraction (RF) data for each particle size, at low and high physical activity levels. The RF is calculated by measuring the difference in mass concentration of particles deposited on the material sample before and remaining on the material sample after the period of resuspension, as a percentage of the mass concentration deposited on the material sample before resuspension. The data is averaged over all contaminated material types. Low physical activity consisted of walking for 20 minutes. High physical activity was representative of running and simulated by modified Irish dancing to a Reel for 10 minutes, as described in section 2.4.

The NAA data indicates that the fraction of particles which are resuspended from the clothing of a person engaged in low physical activity ranges from 8 to 52 %, with an average RF

across all sized particles of 28 ± 8 %. During high physical activity, between 3 and 67 % of particles formerly deposited on various clothing types was found to resuspend, with an average RF value across all particle sizes of 30 ± 7 %. A two-tailed paired T-test shows that the difference between the average resuspended fraction (averaged over all particle sizes and material types) at low and high physical activity level is not statistically significant.

Figure 3 shows the average size distribution of particles in the air surrounding a contaminated person engaging in either low (blue diamonds) or high (red circles) physical activity, as measured by an APS at waist height. The mass distribution is calculated by averaging the total concentration per second in each size range, over the entire physical activity (i.e. resuspension) duration: 20 minutes for low and 10 minutes for high physical activity. This is calculated for each repeated experiment and for each material type (i.e. 16 individual experiments) and an overall average is obtained for each physical activity level.

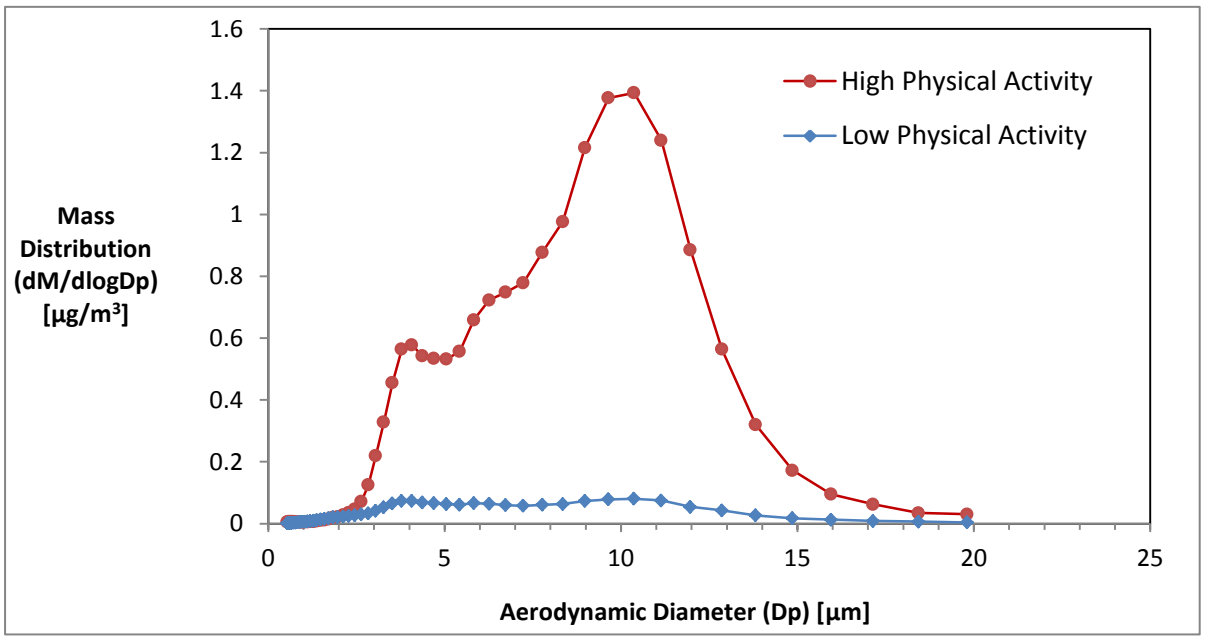

Figure 3. Size distributions of particles during low and high physical activity

The sum of the mass concentration of airborne particles over all particle sizes during low physical activity is 1.72 µg m^{-3} and during high physical activity is 16.93 µg m^{-3}. This is

almost a tenfold increase in the cumulative mass of airborne particles during high physical activity in comparison to that during low physical activity. This difference is statistically significant, with a p-value of 0.000001 based on a two tailed, paired student t-test. Therefore, within the range of particle sizes measured, and between these two physical activity levels, there is a significant difference in the mass of airborne particles resuspended from a contaminated persons' clothing. However, this conclusion is drawn from the APS data and appears to contradict the results from the NAA data. This apparent contradiction is due to the capturing of different features of the resuspension process by the two different analytical techniques, as discussed below.

The APS data shows the airborne mass concentration as a function of particle size and thus measures all particles that are airborne, regardless of their origin. NAA data are used to determine the resuspended fraction (RF), which is calculated by measuring the difference in mass concentration of particles deposited on the material sample before and remaining on the material sample after the period of resuspension, as a percentage of the mass concentration deposited on the material sample before resuspension. Hence the concentration of particles remaining on a sample after resuspension is the key variable in determining the resuspended fraction from that sample. However, this value may be higher than expected due to an unquantified number of particles remaining on that sample after the resuspension event, caused mainly by three processes which are described below.

The first contributor to a higher than expected mass concentration of particles remaining on the material sample after the resuspension event is impaction of resuspended particles back onto the material sample. During resuspension, the volunteer wearing the contaminated clothing is moving vigorously on a fixed position on the floor for a period of time. Thus some particles which are initially resuspended may be re-deposited onto the clothing sample due to

impaction, as the body part is moved through the 'cloud' of resuspended particles. The movement of a body part through a particle-laden airstream which results in impaction, is analogous to the process of particle impaction when a moving particle-laden airstream encounters a stationary object – this process has been well described (e.g. Golovin and Putnam, 1962, Hinds, 1999, Lange, 1995, and Ranz and Wong, 1952).

The second contributor is enhanced deposition due to both increased air velocities around the moving person and the rate of displacements of the body parts (and hence the material samples) themselves. Wu et al. (1992) concluded that, once particles are resuspended from their residing surface, their trajectories depend on the characteristics of the turbulent air flow and not on the initial velocity of the particle. The resuspended particles in this study will have a high velocity due to the increased air velocity caused by the physical movement of the contaminated volunteer. Rim and Novoselac (2009) examined the influence of localised arm movement on air velocities using a mechanical manikin sitting on a chair and the hands were subjected to large and small motion. The large motion was a periodic rotation of the entire arms back and forth by ± 30º (represents active hand movement e.g. filing), the small motion was a periodic up and down rotation of the elbow by ± 10º (represents limited hand movements e.g. typing). They concluded that physical activity of the manikin does significantly affect the air velocity at 20 cm above the floor but does not largely affect the air velocity above the head and also that large motion has a greater affect than does small motion. Bjorn and Nielsen (2002) also investigated the influence of the physical activity of a manikin in a room and found that a larger degree of air mixing occurred in the room with the moving manikin than with a stationary one. The volunteer in the current experiments is moving at a fast pace, for example, during high physical activity (modified Irish dancing) the volunteer jumps from one leg to the other at an average rate of 55 jumps per minute which corresponds to a rate of leg displacement of approximately 0.75 m s^{-1} and a rate of

arm displacement of approximately 0.5 m s^{-1}. This movement will undoubtedly increase the air movement around the active contaminated person and thus increase the resuspended particles' velocity which will lead to enhanced deposition back onto the contaminated material as the material is repeatedly moved through the 'cloud' of resuspended particles.

The third contributor is the penetration of resuspended particles deep into the weave of the material. Because of the particles' increased velocities when they redeposit, they will have an increased kinetic energy and hence may penetrate deeper into the weave pattern of the material. These particles will therefore be more difficult to re-resuspend. This point will be elaborated in section 3.3.

As a consequence of the above three events occurring during resuspension, the mass of particles calculated to be on the clothing sample after the period of resuspension may be higher than would be the case if all particles which initially resuspended were removed and not available to re-deposit. Therefore a lower RF than is actually the case is calculated but it should be noted that this RF is representative of a real-life scenario where impaction and secondary resuspension would be continuously occurring.

The rate of recapture is difficult to quantify, as it is dependent on a number of variables including: air velocity, target velocity, particle size and Stokes number, the boundary layer thickness and Reynolds number. The impact efficiency onto a cylinder for particles with very small Stokes numbers (as is the case here) is difficult to assess as these particles are extremely sensitive to the boundary layer very close to the cylinder (Haugen and Kragset, 2010). According to figure 3 of Wessel and Righi (1988), for a Reynolds number of zero (in this experiment, Re~0.2 around the arm) and a Stokes number of 1.5, the target efficiency will be 50 %. The APS data indicates a 10 fold increase in the mass of airborne particles but only a two fold increase in the number of airborne particles, during low and high physical

activity. Hence, a greater proportion of the smaller particles are being recaptured by the clothing, particularly at higher physical activity levels. This is due to the smaller particles being more likely to remain in the air streams created by the moving body part and thus being intercepted by the body part moving back through the same air location. The bigger particles will leave the air streams and move away from the body part, and are more likely to be captured by the APS or deposit to the floor etc. This is confirmed by the NAA data, where the RF increases with increasing particle size at both physical activity levels but to a greater extent at high physical activity (this will be discussed in greater detail in a succeeding journal article).

3.3 Resuspension with varied contaminated clothing material type

Four different material types were investigated – cotton, polyester, fleece and denim. Each material type was contaminated and worn by a volunteer engaging in physical activity. The concentration of particles resuspended from each material type was investigated, with each material type experiment repeated four times and an average distribution calculated. This was possible as the consistency between data derived from repeated experiments using any one material type was high (all p values ≥ 0.17, i.e. no significant difference).

Figure 4 shows the average mass distribution of airborne particles as a function of particle size, for each material type. The average mass distribution is averaged over the entire resuspension process (10 mins at high physical activity) and over all four repeated experiments of each material type. The size distribution curve for particles resuspended from fleece is represented with blue diamonds, polyester with red squares, denim with green triangles and cotton with yellow circles.

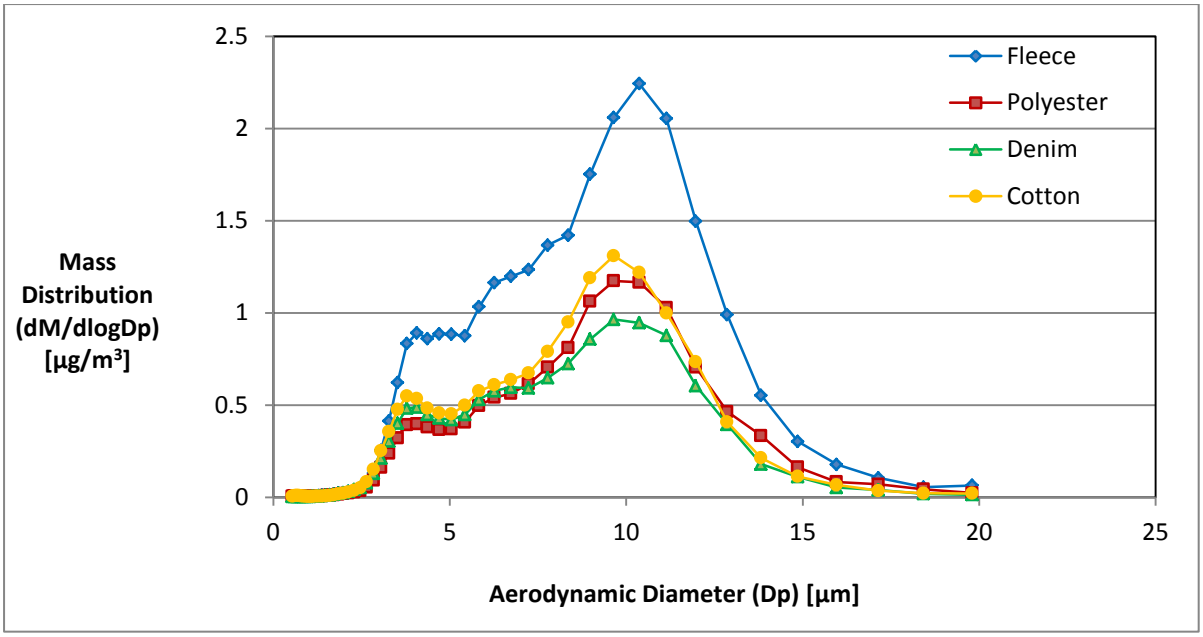

Figure 4. Size distribution curve of particles resuspended from all four material types, during high physical activity

From figure 4 it can be seen that the size distribution curve for particles resuspended from fleece corresponds to a higher mass concentration than that for the three other material types. The cumulative mass concentration of particles of all sizes resuspended from fleece is 26.28 µg m^{-3}, from cotton is 15.13 µg m^{-3}, from polyester is 13.47 µg m^{-3} and from denim is 12.84 µg m^{-3}. Analysing the distributions using a student t-test (two tailed, two samples of equal variance) identifies fleece as being significantly different from the distributions of all other material types, with $p = 0.02$, 0.01 and 0.04 between fleece and polyester, denim and cotton, respectively. However, the distributions of polyester, denim and cotton are not significantly different from each other.

The above finding is confirmed using the data analysed by NAA for the same set of data (figure 4). The average RF for fleece is 41 ± 10 %, for polyester is 31 ± 7 %, for denim is 28 ± 4 % and for cotton is 25 ± 5 %. Using the same statistical test as was used for the APS data, the resuspended fraction of original contaminant from fleece and fleece alone is significantly

different from that of each of the three other contaminated material types, with p = 0.03, 0.005 and 0.001 between fleece and polyester, denim and cotton, respectively.

The above finding may be explained by considering the varied surface texture of the material types. The synthetic fleece used in these experiments is made from 100 % polyester as is the polyester material. However the weave pattern is very different for both material types, as confirmed using SEM imagery (figure 5). The polyester material has a very uniform and tight weave pattern (which, as an aside, is found to be very similar to the weave pattern for membrane collection filters, described by Bénesse et al., 2006) while the fleece is more irregular and loose.

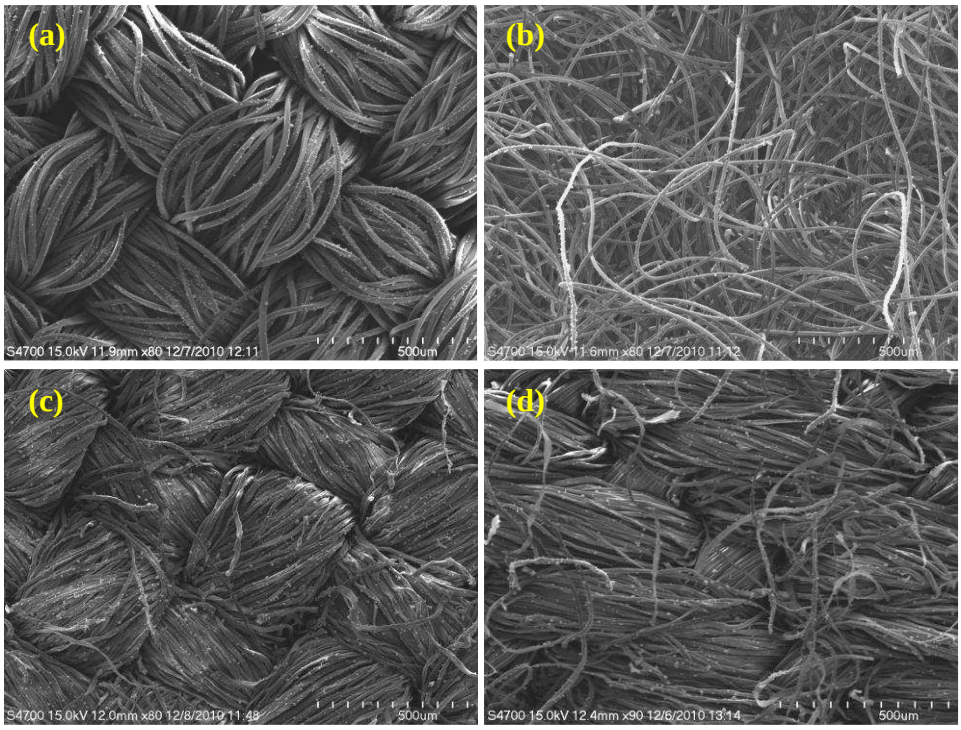

Figure 5. SEM images showing the weave pattern of: (a) polyester (b) fleece (c) cotton and (d) denim. Each image is taken at 80 or 90 times magnification and the scale at the bottom right corner is 500 µm.

Although the majority of deposited particles reside in a monolayer on the surface layer of

the material (as verified using SEM imagery of contaminated surfaces), some particles deposited onto the polyester surface penetrate into the crevices between weave strands and could potentially be trapped there (due to the tightness of the weave) and thus be harder to resuspend. An example of particles deposited deep into the weave can be seen in figure 6. This could account for the degree of resuspension of particles from polyester, cotton and denim (all with the same weave pattern) to be lower than that from fleece.

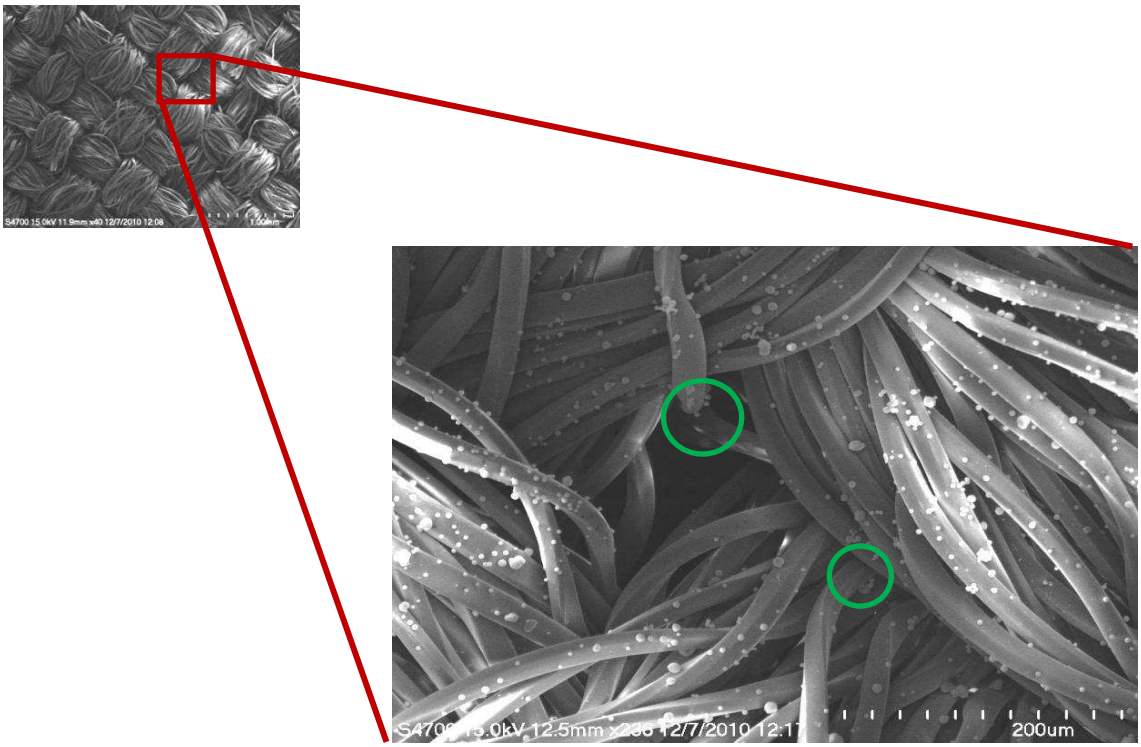

Figure 6. SEM image of particles deposited deep into the weave (circled areas) of contaminated polyester

The APS results in figure 4 and the succeeding discussion of the related NAA data, also indicate that the fibre used to make the cloth or material does not significantly affect resuspension, as the polyester and cotton materials used in these experiments were found statistically to have the same level of resuspension from them. While they are made from different fibres - polyester is synthetic and cotton is natural - they both have the same weave

pattern. This indicates that it is the surface texture roughness and not material type, which is the more important factor in relation to the resuspension of hazardous aerosol particles from clothing surfaces.

Previous findings indicate that increasing surface texture roughness results in lower amounts of particle resuspension, for example, Wu et al. (1992), Braun et al. (2002), Hession et al. (2006) and Andersson et al. (2004), and this appears to contradict the findings in the present work. However, the apparent discrepancy can be explained by considering the relative significance of macroscopic and microscopic features of the fabric. Macroscopically, fleece would have a rougher surface texture than polyester and should therefore demonstrate a lower resuspended fraction which it does not. However, microscopically, the polyester material has a rougher surface texture than the fleece material, due to their respective weave patterns. If one considers that penetration and settling of particles deep into the weave of the clothing fabric (which is occurring in the current experiments due to the increased air velocities around the volunteer from of their physical movement and also due to impaction of airborne particles back onto the clothing samples), then the significance of the microscopic features of the fabric can be realised.

One parameter which may have an influence on particle behavior but which was not investigated in these experiments is static charge. The electrostatic forces associated with surface residing particles, can both aid and hinder particle resuspension and are dependent on a number of factors including the composition of the material subjected to friction, the amount of friction or surface agitation, and the relative humidity of the ambient air.

4. Conclusions

The influence of human physical activity level on particle resuspension from clothing was examined using two analysis techniques: Neutron Activation Analysis (NAA) and Aerodynamic Particle Sizing (APS). The NAA data showed that the average resuspended fraction (RF) of particles at low physical activity was 28 ± 8 %, and at high physical activity was 30 ± 7 %, a statistically insignificant difference. In contrast, the APS data revealed a statistically significant tenfold increase in the cumulative mass of airborne particles during high physical activity in comparison with that during low physical activity. While both techniques indicate an increase in resuspension with increasing physical activity level, the difference in terms of statistical significance is attributed to the two analysis techniques capturing different aspects of the resuspension process, as discussed in section 3.2.

In respect to the influence of the contaminated surface type on particle resuspension, the results obtained indicate 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). Fleece was found to exhibit the highest levels of particle resuspension (cotton, denim and polyester showed no significant difference), as particles did not become trapped deep within the weave pattern of the material and were thus relatively easily released from the non-uniform weave, when the material was subjected to agitation.

An investigation of the change in airborne mass concentrations with time, due to the resuspension of particles from contaminated clothing, revealed that the data was separable into two distinct regimes: the first having a high, positive rate of change of airborne particle concentration relative to the second regime, and occurring within the first 1.5 minutes of the beginning of the resuspension event. The second regime revealed a slower rate of change of particle concentration and remained relatively unchanged for the remainder of each

resuspension event.

In conclusion, based on the variables investigated in this study, the conditions for which the highest fraction of initially deposited particles became resuspended were during the wearing of contaminated clothing of fleece material by a person engaged in a high level of physical activity, and during the first 1.5 minutes of that activity. The finding that physical activity can cause up to 67 % of contamination formerly deposited on clothing to be resuspended back into the air implies that the transport process of resuspension is of considerable importance for accurate determination of human exposure risks.

5. Acknowledgements

This work has been sponsored by the Radiological Protection Institute of Ireland (RPII) and supported by the European Commission under the 7th Framework Programme through the 'Research Infrastructures' action of the 'Capacities' Programme, Contract No: CP-CSA_INFRA-2008-1.1.1 Number 226507-NMI3. Support was also received from The Aerosol Society in the form of a research scholarship: The C.N. Davies award.

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