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Study on Aerosol Penetration Through Clothing and Individual Protective Equipment

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Human Protection and Performance Division
Defence Science and Technology Organisation

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ABSTRACT

Aerosol particles can readily penetrate through air permeable fabrics. Air flow and aerosol deposition models were used to determine the skin deposition rates of aerosols through up to two fabric layers. These models were used in conjunction with a plume dispersion model to examine the risks associated with wearing air permeable CBR protective clothing, to inform IPE fabric development programs and allow assessment of aerosol protection requirements.

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Executive Summary

Aerosol particles, either liquid or solid, behave differently in air flows when compared to gases and vapours. Gases or chemical vapour are captured by the activated carbon adsorbent in air permeable protective fabrics, however aerosols can couple to air flows which can carry aerosols through the porous structures of air permeable fabrics.

Air permeable chemical protective fabrics are used in both in-service chemical biological radiological (CBR) protective garments; the MkIV Overgarment and the low thermal burden black chemical biological (CB) suit. The level of risk associated with plume dispersed CBR aerosols (those released outside and carried by the wind) was quantified by modelling the amount of aerosol which penetrated IPE and deposited on the skin. This risk level will then inform IPE fabric development programs and allow assessment of aerosol protection requirements.

A software program was developed using simple air flow and aerosol deposition models to evaluate the threat posed by aerosolised agents through up to two layers of clothing. Three relevant clothing ensembles were evaluated using the models; the MkIV Overgarment, the black CB suit with DPCU shirt underneath, and black CB suit as a standalone garment. As the clothing layers were highly complex, fabric characteristics were generated by fitting an aerosol penetration model to experimental data of aerosol penetration through fabric swatches.

Results showed that the volume of air that flowed through the fabric layers was relatively small, which limited the total amount of agent which could move through the fabric and deposit on the skin. Additionally, the deposition rate of particles on the skin was low for the particle sizes that penetrate the fabric, as the physics that allows aerosols to penetrate through fabrics, also couples the aerosols to the air flow as it exits. This means that even though the fabrics had a high penetration of aerosols during swatch tests (of up to 95% of particles), less than a few percent deposited on the skin.

To show the risks associated with the aerosol penetration and deposition on the body, two highly engineered, weaponised aerosol threat scenarios were evaluated, using plume dispersion modelling.

Both scenarios demonstrated that respiratory protection is paramount against aerosolised threats, as deaths would occur in both cases without any protection.

Scenario 1 was a release of 50 kg of an aerosolised nerve agent, and modelling predicted that when wearing any of the three clothing ensembles, the dose deposited on the skin would be well below the assumed LD_{50} level.

Scenario 2 was a 1 kg release of Anthrax. Modelling showed high enough deposition on the clothing to be a decontamination risk, but this would be easily managed with appropriate doffing and decontamination procedures. The dermal contamination predicted was very low, and was not considered a significant dose as the Anthrax must be inhaled in large enough amounts to cause infection.

While aerosols could be a skin hazard due to penetration through protective clothing, a number of factors need to be considered when assessing vulnerability:
- The aerosols would have to have a very precisely engineered range of particle sizes;
- The agent would have to present a hazard through skin contamination in small doses;
- The design of such an agent may conflict with other characteristics desirable in a CBR weapon such as particle sizes in the "breathable range", or easy dissemination in large quantities;
- Weather conditions needed to maximise aerosol penetration through clothing, such as high winds, may not be optimal for producing high concentrations of agent via plume dispersion; and
- Such a release would only produce low deposition rates on the skin, and potentially some injuries.

This suggests that such a threat could be considered unrealistic as a huge amount of effort would be required for little effect.

The modelling produced data based on a cylindrical body with consistent air gaps between layers, and no air gaps due to closures. To confirm the aerosol penetration behaviour on a moving human body, experiments using an articulated manikin will be completed when the equipment becomes available in 2009/2010.

The data presented in this report suggests that the penetration of aerosolised agents through the air permeable fabrics of in-service IPE does not constitute a significant hazard. Thus there would not seem to be an imperative to increase the aerosol protection of these fabrics particularly if any changes were to affect the user comfort level or chemical vapour/liquid protection levels. Further work could identify potential aerosol hazards to the IPE that are not considered here, for example indoor aerosol releases and aerosol penetration through seams and gaps in IPE.

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Dr Jamriska joined DSTO in 2005 to establish and support CBRN aerosol R&D capabilities. His current work is focused on characterisation of IPE, barrier fabrics and respirators, performance against airborne CBRN threats and development of new IPE materials. Other areas of his research include T&E and R&D of aerosol sampling devices and development of new detection methods for aerosols of biological and non-biological origin.

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Contents

1. Introduction

Using the turbulent mixing action of the wind is a common method to disperse Chemical, Biological and Radiological (CBR) agents into the environment. If an agent occurs as a gas under normal environmental conditions then the wind will efficiently distribute it. If the agent occurs as a solid or liquid then it must be aerosolised as particles or droplets. If the aerosols are sufficiently small then the effects of wind dispersion will be very similar to that of a gas. Even small aerosols will however differ from gases in the way that they interact with air permeable materials. The differences arise in the ways that aerosols couple to air flows which can carry them through the porous structures of air permeable fabrics.

This behaviour of aerosols has a range of implications for the threat posed by aerosolised CBR material. The aerodynamic characteristics of the aerosol will affect the probability of particles penetrating through air permeable fabrics used in clothing or Individual Protective Equipment (IPE). Air flow through these fabrics reduces the heat stress imposed by the clothing or IPE but also allows a potential pathway for contamination by aerosolised agents.

1.1 Scope of this report

The goal of this work was to quantify the risk from plume dispersed CBR aerosols that penetrate IPE and clothing to deposit on the skin. This risk level will then inform IPE fabric development programs and allow assessment of aerosol protection requirements.

Simple mathematical models of the physical processes involved were used to assess this risk. These models describe the flow of air into and out of layers of air permeable clothing, the filtration of the aerosols in the clothing layers and the deposition of aerosols on the clothing and the body.

A software program has been developed that incorporates the air flow model and the aerosol fabric penetration and deposition models. The program provides a measure of the rate of aerosol deposition on the body for specified clothing parameters, aerosol threat and environmental conditions. As the physical characteristics of a fabric will determine its response to an aerosol threat, measurements relevant to aerosol penetration of some fabrics in use by the Australian Defence Force (ADF) were included.

Finally we examined the implications of aerosol penetration by using a hazard modelling program to simulate a number of CBR agent releases into the atmosphere. The software program was used to predict the level of skin exposure that would result from the releases.

2. Aerosol characteristics

Aerosol science is a large field with a wide range of applications. Here we will consider only the few characteristics of aerosols that will affect our aerosol fabric penetration model. Hinds (1999) provides a useful aerosol reference that is often referred to in CBR aerosol studies. Hinds defines aerosols as "…a collection of solid or liquid particles suspended in a gas". The size and shape of the aerosols will depend on the material and the method of aerosol generation. The aerosol descriptions given here and the filter model used later are taken from Hinds.

The fundamental parameter that describes aerosol behaviour is the particle size, defined here as the particle diameter, d. For the models used in this report we assume that the aerosols are spherical. For liquid aerosols, which naturally form spheres due to surface tension, this is a valid assumption. Roughly symmetrical solid particles should also be described well by the models, however if the shapes of the aerosols are very asymmetric, such as fibres, the models will probably not be accurate. In addition to particle size, the density of the aerosol material will also affect how it moves in an air flow and how it responds to gravity.

One of the properties that distinguishes aerosols from gases is that of adhesion. Aerosols tend to stick to surfaces they touch due to van der Waals forces. In this work we will assume that all aerosol particles that impact on fabric fibres or other surfaces will stick and be permanently removed from the air flow.

There are some aerosol properties that could be exhibited that will not be considered here. We will assume that aerosols released into the air will not change in size due to evaporation or agglomeration. These effects would need to be considered in detail for specific materials and release scenarios. We will further assume that the amount of aerosol deposited in fabrics does not lead to "clogging" of fabric pores. Clogging effects are complicated and introduce non-linear time dependent effects into the air permeability of the fabric and its filtration characteristics. In most realistic outdoor release scenarios of CBR agents the aerosol concentration would not be high enough to cause clogging.

The effect of electrical charge on aerosols is not addressed in this report. Detailed modelling of charge effects would require an understanding of the nature of the agent, the dispersion mechanism, charge decay in the atmosphere and the electrical properties of the fabric and the human body. As with diffusion, we would expect aerosol charge to increase the mobility of aerosols in the air flow leading to an increase in both fabric filter efficiency and deposition efficiency on the body. In general we find, for fixed air flow conditions, that increasing the aerosol diffusivity reduces the overall rate of aerosol deposition on the body. In effect the filtration efficiency of the fabrics increases more rapidly than the deposition efficiency on the body as the diffusivity of the aerosols is increased. We expect similar behaviour from increased aerosol mobility due to charge effects.

3. Fabric characteristics

This study used three relevant in-service ADF fabrics: the current disruptive pattern combat uniform (DPCU) shirt worn by Army, the Black CB fabric used in the low thermal burden chemical biological combat suit worn by the Incident Response Regiment; and the NBC No.1 MKIV Overgarment (MkIV), the ADF in-service CBR IPE suit. The physical description of these fabrics shows that the Black CB and MkIV are not simple materials but contain multiple components in the fabric layers, and the MkIV has multiple layers.

Table 1:   *A physical description and composition of the three test fabrics in this study*

Fabric	Appearance		Fabric construction	Air Permeability $(m.s^{-1}.Pa^{-1})$	Thickness (mm)
DPCU shirt	Single layer		Plain weave	1.48×10^{-3}	0.6
Black CB	Single layer trilaminate	Outer	Single knit	4.78×10^{-3}	1.8
		Middle	Activated carbon spheres		
		Inner	Double knit		
MkIV	Two layers	Outer layer	Twill weave	2.76×10^{-3}	0.8
		Inner layer	Non woven cloth bonded to a scrim coated with activated carbon	1.92×10^{-3}	2.0

The physical characteristics of these fabrics are listed in Table 1, where air permeability (AS 2001.2.34-1990) and thickness (AS 2001.2.15-1989) were measured in accordance with Australian Standards. The temperature and humidity values specified in the standards were not strictly followed but were typical of indoor laboratory conditions. The measured values of air permeability, which is the parameter in Table 1 that will most affect aerosol penetration, are in good agreement with manufacturer supplied values.

Air permeability, Γ, relates the pressure drop, ΔP, across the fabric to the velocity, V, of air flowing through fabric

$$V = \Gamma . \Delta P$$

The textile standard (AS2001.2.34-1990) quotes the air permeability at a pressure drop of 100 Pa. Additional air permeability values at different pressure drops were also measured (ASTM D 737-96) and these confirmed the linearity of air permeability over the pressure drop range considered in this report (Appendix A).

3.1 Fabric filter characteristics

The fabrics of clothing layers will act as filters, trapping some aerosol particles and allowing others through. It is tempting to think of the fabric as a sieve, which traps particles that are larger than the size of the pores in the fabric. In fact the filtration behaviour is due to the coupling of aerosols to the air flow around the fibres of the fabric, which can be described using single fibre filtration theory (Hinds 1999). This theory predicts the efficiency of trapping aerosols of given size by individual fibres, which can then be used to predict the bulk filtration properties of a fabric. The main mechanisms that contribute to the trapping of aerosols are shown in Figure 1.
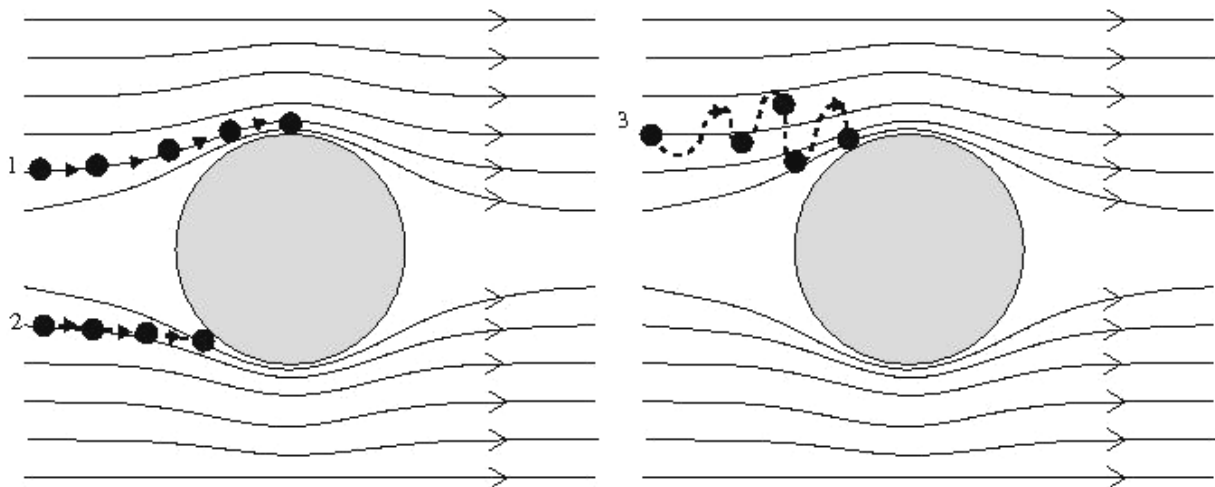

Figure 1: The three most important aerosol trapping mechanisms when aerosols (small black circles) follow the air flow around fabric fibres (large grey circles). Case 1 shows an aerosol of intermediate size as it follows the air flow but impacts with the fibre because of the aerosol physical size. Case 2 shows a heavy aerosol, it has sufficient momentum to decouple from the air as it flows around the fibre. Case 3 shows a light aerosol where the thermal diffusive motion (Brownian motion) causes it to decouple from the airflow and contact the fibre.

Three parameters are used to characterise the filtration behaviour of a fabric; fibre diameter, fabric thickness and fabric solidity (solidity = 1-porosity). Single fibre filtration theory represents the behaviour of an ideal fabric. In practice the air filtration characteristics of fabrics result from a complex interaction between factors such as the fibre sizes, the weave type and density and the fabric thickness. In particular, the size distribution and alignment of the fibres in a real fabric lead to filtration behaviour that differs from that described by theory. Additionally the Black CB and MkIV fabrics are multi-layered materials that are difficult to describe by the single fibre theory.

The approach followed here was to use filtration theory to provide a "fitting" function that reproduced the filtration behaviour measured in the laboratory. The real fabric fibre diameter and solidity were replaced with "effective fibre diameter" and "effective solidity" such that the single fibre model best represented the measured filtration behaviour of each fabric (Table 2). More details of the measurement of the fabric filtration behaviour and the fitting of this data to the single fibre model are given in Appendices A.2 and A.3.

Table 2:   Summary of parameters for different clothing and IPE types

Fabric		Effective fibre Diameter (μm)	Effective solidity
DPCU shirt		11	0.05
Black CB		23	0.08
MkIV	Outer	15	0.05
	Inner	15	0.05

4. Model of airflow through clothing layers

4.1 Pressure model

The foundation for understanding the threat of aerosol penetration through clothing is a model for air flow around a human body. This air flow can be caused by an ambient wind but also the movement of the body through the environment. The flow of air causes pressure gradients across the layers of clothing that surround the body, which cause air to flow through the clothing carrying aerosols from the external environment into the gaps between the layers of clothing.

For mathematical simplicity the pressure model, shown in Figure 2, assumes that the human body is a simple cylinder surrounded by cylindrical layers of clothing. The model is described by 6 parameters; wind speed, radius of the body, the size of the air gaps between clothing layers and the air permeability of the 2 clothing layers. The details of the pressure model, including its assumptions and limitations, are given in Appendix B.

Using this simple model, the air pressure distribution around the body and within the clothing gaps can be calculated (Figure 3). Also shown is the velocity of the air flow through the fabrics. The environmental conditions and the fabric types and clothing geometries used in the model to generate Figure 3 and Figure 4 are given in Table 3.

Table 3:   Parameters used to generate the pressure and air flow plots shown in Figure 3 and Figure 4

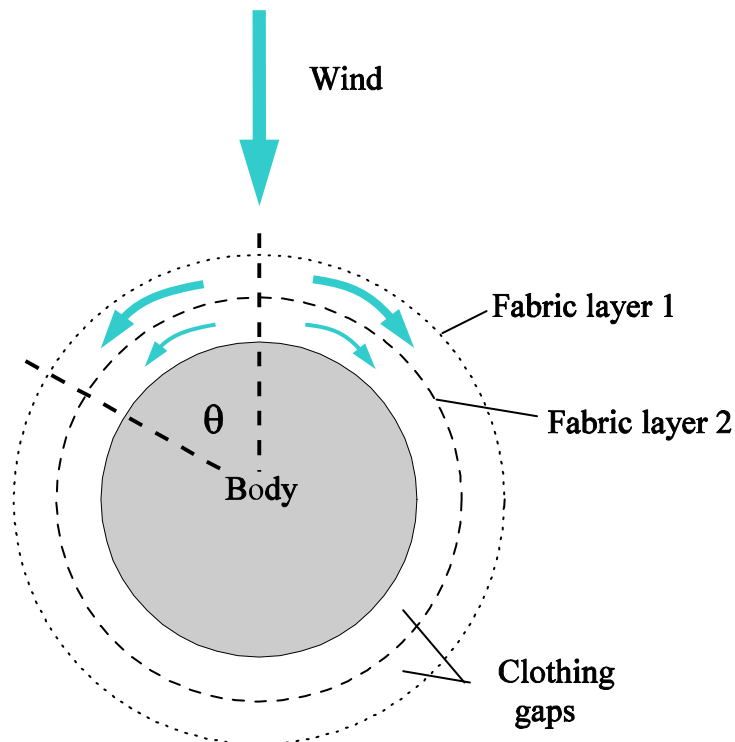|	
Wind speed	5 m.s^{-1}
Body Radius	15 cm
Fabric layer 1 (outer)	MkIV outer
Air gap width	2 mm
Fabric layer 2 (inner)	MkIV inner
Air gap width	2 mm

Figure 2:   Air flow model of a body covered with 2 layers of air permeable clothing. The variation of pressure and through-fabric velocity are described in terms of θ, the angle around the body (θ = 0 corresponds to the direction of the wind).

The air flow into the layers of clothing is fastest at the front of the body, reduces away from the front of the body and becomes zero at some point at the side of the body (Figure 3). After this point the air flows out of the clothing gaps and back into the environment. The pattern of air flow is important in understanding the threat from air dispersed aerosols as the air flow that carries aerosols into clothing layers may also carry them back out again. The contamination threat comes from those aerosols that deposit inside the clothing layers and on the body. The rate of aerosol deposition is dependent on the volume flow rate of air through the clothing gaps (Figure 4). A model for the aerosol deposition rate is discussed in the next section.
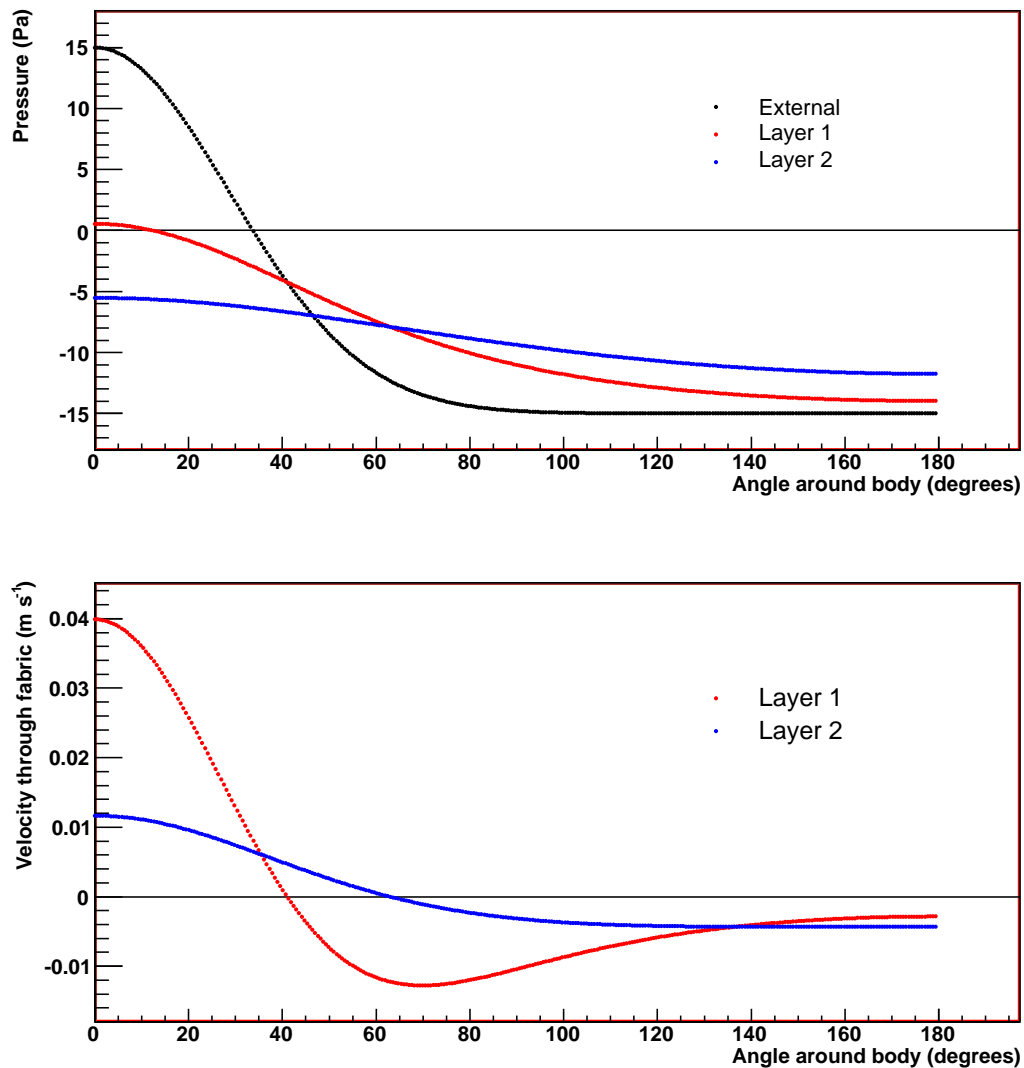
Figure 3: *Top plot: Pressure drop across the 2 clothing layers. Bottom plot: velocity of air flow through the clothing layers. The bottom plot shows that the air flows into the clothing gaps at the front of the body (the part of the body facing directly upwind). The air flows around the clothing gaps and exits at the back of the body.*
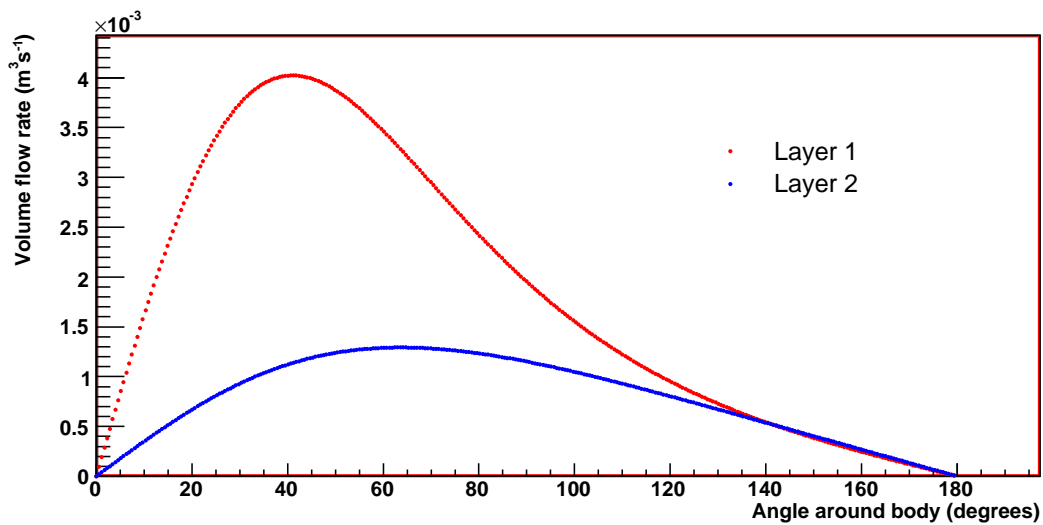
Figure 4:   The volume flow of air through the 2 clothing gaps. The volume flow is important because it determines the amount of aerosol laden air that is brought into the clothing gaps from outside. The flow rate also plays an important part in determining the rate of aerosol deposition.

4.2 Aerosol deposition model

As the air flows through the clothing gaps diffusive movement of the aerosols will cause some of them to contact the fabric and body surfaces that form the walls of the gaps. These aerosols will adhere to the surfaces and be removed from the air flow and it is this mechanism that causes aerosol deposition on the body. If we treat the clothing gaps as being parallel channels then we can easily calculate the fraction of aerosols that will deposit (see Appendix C).

This calculation shows that the deposition rate is small. For the aerosols that are typically most penetrating (0.3 μm diameter), less than 1% of the aerosols will deposit for the typical conditions that the air flow model predicts. The same physical processes that allow aerosols to pass through a fabric also carry the aerosols past the body and fabric surfaces. This has strong implications for the threat that aerosolised agents pose as a body contamination hazard.

The low deposition rate can be understood by considering the thermal motion of aerosol particles in air. Typical displacements of aerosols in one second under standard atmospheric conditions are shown in Table 4. These data show that in the time an aerosol spends in a clothing gap (< 1 s), it will not move significantly relative to the air flow that carries it.

This conclusion, that few of the aerosols in the gaps will deposit, is supported by other work (Fedele 1992), even though different assumptions about the mechanism of deposition were used. It is possible that the complicated air paths that occur in real clothing will lead to higher aerosol deposition rates than the simple parallel plate model used here. However, it is difficult to see how simple changes to the geometry of the gaps could cause a significant fraction of the aerosols to deposit.

Table 4:   *Net displacement in 1 second for spheres with water equivalent density under standard conditions. Data from Hinds (1999).*

Particle diameter (μm)	RMS Brownian Displacement in 1 second (m)	Gravitational settling in 1 second (m)
0.01	3.3×10^{-4}	6.9×10^{-8}
0.1	3.7×10^{-5}	8.8×10^{-7}
1.0	7.4×10^{-6}	3.5×10^{-6}
10.0	2.2×10^{-6}	3.1×10^{-3}

5. Software program

The processes that contribute to the rate of aerosol deposition on a clothed human body have been discussed in previous sections. The effects of these processes need to be combined to estimate the overall threat posed by aerosolised agents. To accomplish this we have written a software program that incorporates the physical models discussed previously. This program was written in the C++ programming language. An executable version of this program has been developed that runs under the Windows operating system and so allows an operator to change the parameters of the model via a graphical user interface (Appendix D).

 The threat environment is specified by selecting the wind speed and aerosol characteristics; aerosol density, size and concentration. The width and height of the cylindrical body are also specified. The program models up to 2 layers of clothing over the body. The layers are described by the width of the clothing gap and the fabric permeability. The filter characteristics of the fabrics are parameterised by the fabric thickness, the effective fibre diameter and the effective fabric solidity (as described in Section 3.1). The layers of clothing are individually configurable. It should be noted that the software program does not calculate the amount of aerosol that directly deposits on the outside of the outer layer of clothing.

As discussed in Section 4.1, the software program produces graphical output which shows the air pressure in the clothing gaps (Figure 3) and the air flow through them (Figure 4). The software also produces outputs of the concentration of aerosol in the clothing gaps, and the rate of collection of aerosols by the filtration action of the fabrics (Figure 5), as well as the aerosol deposition rate in the fabrics and on the body (Figure 6). An example output of the program for the MkIV fabrics using the configuration given in Table 3 and Table 5 is provided in Figure 5 and 6.

Table 5:   *Configuration information used by the software program (in addition to the information used in Table 3*

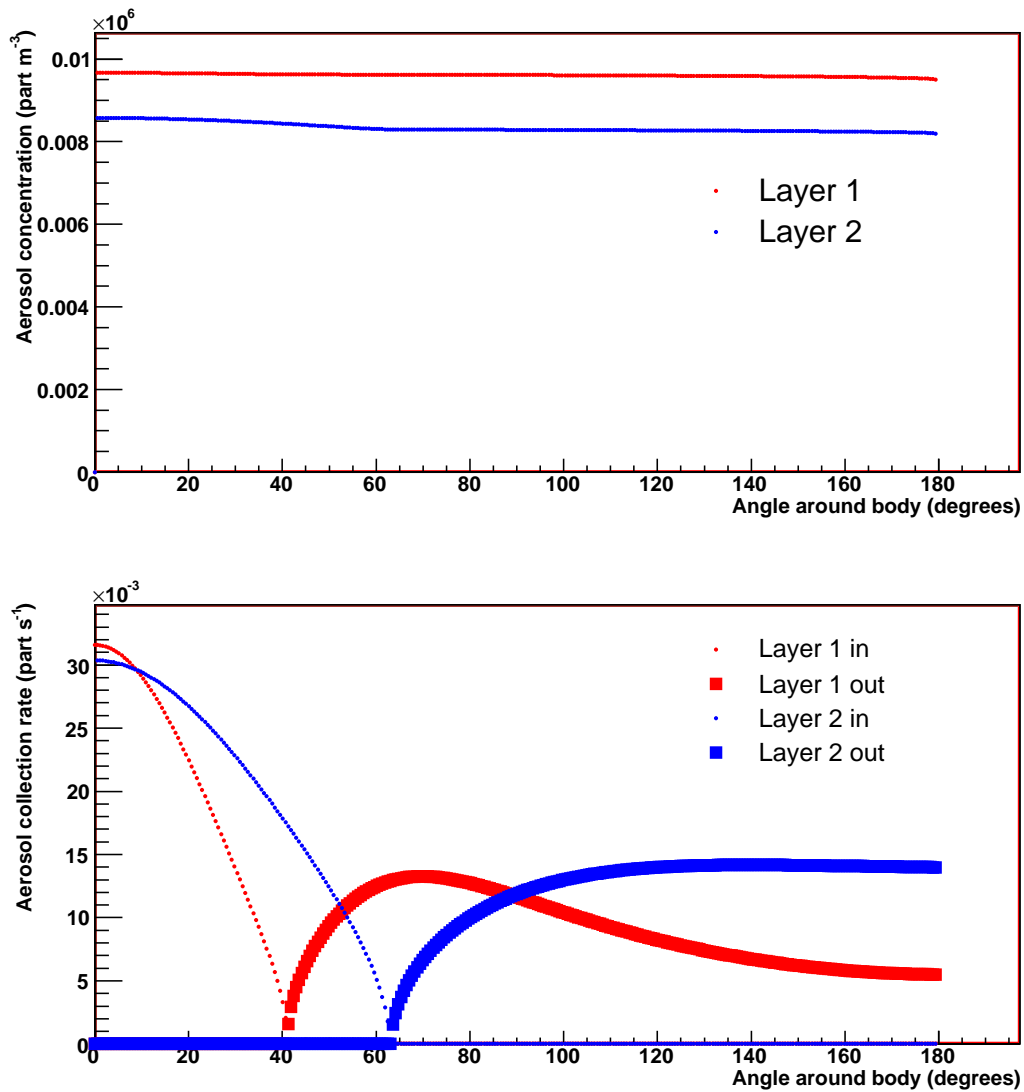| Aerosol parameters	
Diameter	1.0 μm
Density	1000 kg.m^{-3}
Concentration	$10000 \text{ particles.m}^{-3}$
Body configuration	
Height (w/o head)	1.6 m

Figure 5:   Example of the output of the software program. The top plot shows the concentration of aerosols in the clothing gaps. The bottom plot shows the rate of collection of aerosols by the filtration action of the fabrics, shown separately for air flow in to and out of the clothing gaps.
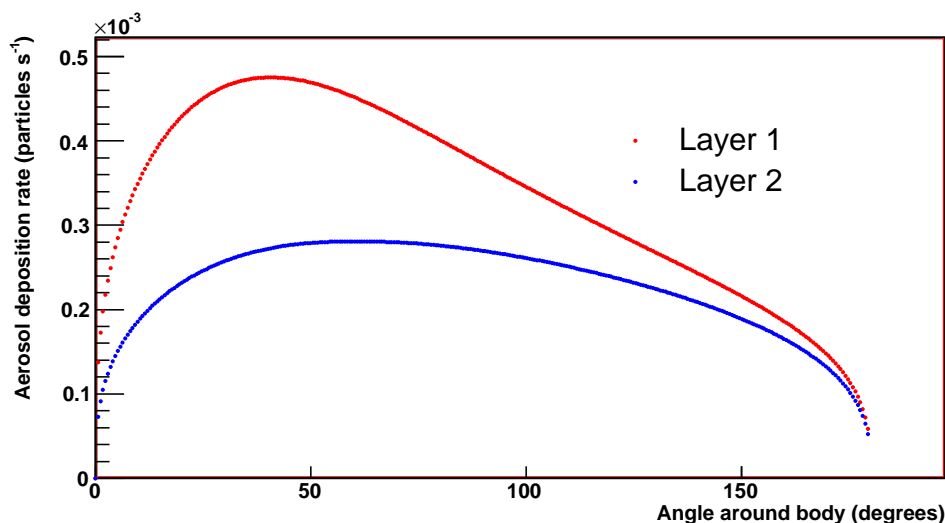
Figure 6: *The rate of deposition of aerosol particles around the body in each of the clothing gaps. It is assumed that the deposited material would be distributed equally between the inner and outer surfaces that form each gap.*

In addition to graphical output, the software program also produces a text summary output of important parameters.

6. Operational examples

When assessing the overall risk posed by aerosol penetration of clothing, the nature of possible releases needs to be considered. As well as the ground level wind speed, other environmental factors will determine the concentration of aerosols relative to the release point. The amount of material released and the type of agent will also have a direct influence on the hazard level.

To investigate the effect of aerosols on dermal protection, we have simulated two scenarios where aerosolised agents are released into the atmosphere. A hazard modelling program developed in the UK, called the Chemical Biological and Radiological Virtual Battlespace (CBRVB), was used in these simulations. The CBRVB uses plume dispersion techniques to predict how material that is released into the atmosphere will disperse in the environment. The CBRVB allows us to specify the environmental conditions and the mass and physical characteristics of a released agent giving a prediction of the concentration of a released agent at different positions relative to the source. This concentration information can be used as an input to the aerosol software program. The result is a prediction of the mass of agent deposited on the body for a given scenario.

A characteristic of plume dispersion from a point source is that the spatial variation in concentration is very strong. Typically the concentration of dispersed material is strongest in the downwind direction near to the source. Even a small release can give rise to very high

concentrations near the source. This complicates the determination of the maximum hazard concentration. Here we used an approach developed by the UK to calculate the maximum effective exposure to a plume dispersed hazard. Firstly we designated a 4 km by 4 km region around the source. We assumed that 5% of this area would be lost; that is we did not expect IPE to protect individuals in this area. The maximum effective exposure E_{ME} was defined as the maximum exposure outside of the 5% area.

For the release scenarios considered here we assumed that the weather conditions were very stable, which is a worst case scenario. These conditions would usually happen at night and mean that there is little vertical movement of air from ground level, maximising the ground level concentration of the plume dispersed material. The weather conditions used in the CBRVB simulation were:

- Surface level wind speed = 1.5 m.s^{-1}

- Surface temperature = 283 K

- Stability condition = F (very stable) [1]

The wind speed specified for plume dispersion would be the same as that for the aerosol penetration model if the body was stationary. We also considered a situation where the body was moving, giving a total relative wind speed of 5 m.s^{-1}.

Three clothing ensembles were considered:

Ensemble A (MkIV)   - outer layer MkIV camouflage layer
                    - inner layer MkIV carbon layer

Ensemble B   - outer layer Black CB suit
                    - inner layer clothing made from DPCU Shirt material

Ensemble C   - same as ensemble B but with no shirt underneath the Black CB suit
                    - no inner layer

The configuration of the body and the clothing gaps are given in Table 3 and Table 5.

6.1 Scenario 1

A release of 50 kg of nerve agent released as an aerosolised particle with a narrow particle size distribution of ≈0.3 μm. The source was located 2 m above ground level and released over a period of 50 seconds. As a worst case, we assumed that the toxicity of the agent is such that LD_{50}=10 mg for a body mass of 70 kg. It was assumed that the agent had a density of 350 kg.m^{-3}, and that it would not vaporise over time. This agent is imaginary and would represent a very highly engineered threat.

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[1] See Gailis, R. M. and G. Fulford (2001)

The CBRVB simulation predicted that E_{ME} would be 760 mg.s.m^{-3} (13 mg.min.m^{-3}), equivalent to an average concentration over a 30 minute period of 0.42 mg.m^{-3} (8.5×10^{10} particles per cubic metre of air). For a body unprotected by IPE we would expect some nerve agent poisoning effects at this exposure level, and without respiratory protection this would include some deaths.

Table 6 gives a summary of the contamination levels predicted by the aerosol penetration software program for this scenario. The amount of material deposited directly on the skin was much lower than the LD$_{50}$ dose of 10 mg for all three clothing ensembles. The predicted doses of ~1-10 µg on the skin are unlikely to cause threshold effects which would require medical attention. These data show that the mass of agent that was deposited in the fabric of the clothing layers was also rather small. As noted previously, the software program did not calculate the amount of aerosol that deposited directly on the outside of outer garment.

Table 6: *Summary of the mass of agent collected in each layer of clothing by filtration and deposition for scenario 1 at two different wind speeds. Also shown is the mass of agent accumulated on the body by deposition.*

	Ensemble A		Ensemble B		Ensemble C	
Wind speed (ms^{-1})	1.5	5.0	1.5	5.0	1.5	5.0
Mass in layer 1 (mg)	0.24	0.73	0.4	1.3	0.4	1.3
Mass in layer 2 (mg)	0.18	1.1	0.15	0.66	N/A	N/A
Mass on body (mg)	0.0024	0.013	0.0033	0.013	0.0078	0.021

6.2 Scenario 2

A release of 1 kg of weapons grade powdered anthrax. The agent was released from a height of 2 m above ground level over a period of 50 seconds as a dust with a narrow distribution of particle sizes centred on 5.0 µm. It was assumed that the anthrax was very pure, containing 10^{12} spores per gram of agent, and that the density of the powdered anthrax was 500 kg.m^{-3}. For anthrax inhalation we will assume that the LD$_{50}$ dose is 10000 spores.

The CBRVB simulation gave an E_{ME} of 15.0 mg.s.m^{-3} (0.25 mg.min.m^{-3}), equivalent to an average concentration of 8.4×10^{-3} mg.m^{-3} (2.57×10^{5} particles per cubic meter of air) over a 30 minute period.

This scenario represents a very high end threat with a large release of a pure agent with a highly engineered particle size. In the scenario, the inhalation LD$_{50}$ dose of anthrax would be exceeded in less than 1 minute. More than the inhalation LD$_{50}$ dose is collected in the clothing layers (Table 7) which could present a doffing/decontamination hazard if the particles were re-aerosolised. A detailed study of this hazard is beyond the scope of this report.

Table 7: *Summary of the mass of agent collected in each layer of clothing by filtration and deposition for scenario 2. Also shown is the mass of agent accumulated on the body by deposition. The number of anthrax spores represented by each mass is also given.*

	Ensemble A		Ensemble B		Ensemble C	
	Wind speed (m.s^{-1})		Wind speed (m.s^{-1})		Wind speed (m.s^{-1})	
	1.5	5.0	1.5	5.0	1.5	5.0
Mass in layer 1 - (mg)	0.0063	0.083	0.0013	0.017	0.0013	0.017
- (spores)	6.3×10^6	8.3×10^7	1.3×10^6	1.7×10^7	1.3×10^6	1.7×10^7
Mass in layer 2 - (mg)	2.8×10^{-3}	0.023	2.9×10^{-4}	1.9×10^{-3}	N/A	N/A
- (spores)	2.8×10^6	2.3×10^6	297900	1.9×10^6	N/A	N/A
Mass on body - (mg)	3.9×10^{-6}	6.1×10^{-6}	5.3×10^{-7}	6.1×10^{-7}	1.6×10^{-6}	2.1×10^{-6}
- (spores)	3919	6135	532	612	1587	2081

7. Conclusions

The threat posed by aerosolised agents that penetrate through air permeable clothing layers has been evaluated using simple air flow and aerosol deposition models. A software program was developed that predicts skin contamination levels based on the aerosol threat, the environmental conditions and the fabrics used in the layers of clothing. Two operational examples of the release of agents into the atmosphere were presented. These examples used plume dispersion models to predict the concentration levels that constituted the aerosol threat. The aerosol software program was then used to calculate the rate of deposition of these agents on the skin for three relevant clothing ensembles.

The results of the work presented here indicate that the fraction of aerosols in the environment that deposit on the body is low, despite the fact that aerosols of the right particle size will easily penetrate through air permeable fabrics. There are two factors in particular which act to limit the aerosol deposition rate. The first is that the volume of air that flows through the fabric layers is relatively small. This limits the total amount of agent that could possibly deposit on the skin. Secondly, the rate of aerosol deposition is low for particle sizes that can penetrate through fabrics. Typically, less than a few percent of the aerosols that enter the clothing gaps will deposit. The rest follow the air flow that exits the layers of clothing: the physics that allows aerosols to couple to air flows and penetrate fabrics also couples the aerosols to the flow as it leaves the clothing gaps.

There are a number of other factors that need to be considered when assessing vulnerability to an aerosolised agent that has been designed to penetrate IPE clothing:
- The aerosols would have to have a very precisely engineered range of particle sizes.
- The agent would have to present a hazard through skin contamination in small doses.
- The design of such an agent may conflict with other characteristics desirable in a CBR weapon; particle sizes in the "breathable range", an agent that could be easily disseminated in large quantities etc.
- Weather conditions needed to maximise aerosol penetration through clothing, such as high winds, may not be optimal for producing high concentrations of agent via plume dispersion.

The two scenarios presented here represent the high end of the threat posed by weaponised aerosols. Both scenarios demonstrated that respiratory protection is paramount against aerosolised threats as deaths would occur in both cases without any protection. Both scenarios also showed that very low amounts of aerosols were deposited on the skin.

Scenario 1, with a release of an aerosolised agent with high toxicity, showed that when wearing any of the three clothing ensembles, the dose deposited on the skin would be well below the LD_{50} level.

Scenario 2, with a release of Anthrax, showed high enough deposition on the clothing to be a decontamination risk and could be managed with appropriate decontamination procedures. The dermal contamination was low, and would not be considered a significant dose as the re-aerosolised Anthrax would have to be inhaled in large enough numbers to cause infection.

The two scenarios were at the high end of likely threats, and did not show casualties. A more comprehensive analysis could be undertaken to study a wider range of threat scenarios and clothing ensemble characteristics. This could include a study of indoor release scenarios as well as the examination of the effects of aerosol charge. Clothing ensemble effects such as aerosol penetration through clothing gaps and seams could also be investigated. These studies may show that under certain circumstances the aerosol threat is enhanced. However, the conclusion of this report is that based on our current understanding aerosols can be considered a low risk when it comes to dermal contamination through air permeable fabrics.

8. References

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Appendix A: Fabric characterisation

A.1.   Air permeability

The air permeability of the tested swatch samples was measured using an FX 3300 Air Permeability Tester III for twenty samples. The relationship between air permeability and pressure differential (pressure drop across the tested fabrics) in the range of 25-100 Pa was evaluated and the average ±STD values calculated (AS2001.2.34-1990 1990). Fabric thickness was also measured (AS2001.2.15-1989 1989).
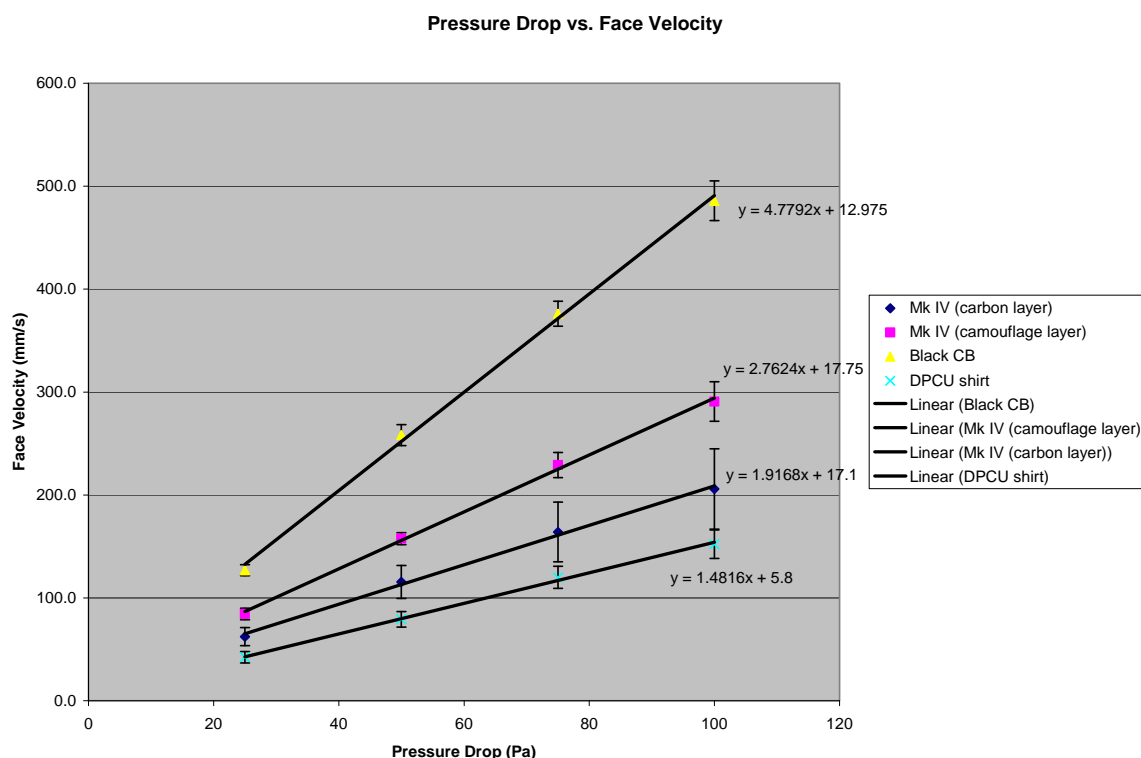

Figure 7:   Permeability measurements for the fabrics considered in this report

A.2.   Fabric filter measurements

Aerosol penetration, *P*, represents the fraction of challenge material which penetrates through tested fabrics. It is calculated from particle concentration measured downstream (C_{Dw}) and upstream (C_{Up}) of a tested swatch sample as $P=C_{Dw}/C_{Up}$.

Aerosol penetration was measured using the DSTO designed aerosol swatch test rig which was based on the ASHRAE 52.2-1999 Standard for both the equipment and methodology, where the standard was modified to allow fabric swatch sample testing.

Swatch samples were tested with NaCl and Di-Ethyl-Hexyl-Sebacate (DEHS) challenge, generated by a Colison nebuliser producing polydisperse aerosols. The aerosols were charge neutralised and dried (passing through a radioactive source and silica drier) before entering ASTER. The swatch samples were measured at air face velocities 0.05, 0.1 and 0.25 m.s^{-1}, representing conditions likely to occur due to winds in an outdoor environment.

Isokinetic air sampling was applied and the effect of aerosol losses in sampling lines and other parts of the test rig were incorporated in analysis.

Aerosol characteristics (size distribution and concentration) were measured by two instruments: (i) Scanning Mobility particle Sizer (SMPS TSI) for particles in 0.03-0.7 µm size range; and (ii) Aerodynamic Particle Sizer (APS TSI 3321) for particles in 0.7-20 µm size range. The results were merged using TSI Merge software.

Typically, swatch penetration was assessed for aerosol challenge levels of 5×10^4 particles.cm^{-3} and 5×10^2 particles.cm^{-3} for SMPS and APS respectively. A dilution system was applied for APS measurements (both upstream and downstream sampling) to eliminate the effect of particle coincidence occurring at high concentration levels. The Count Median Diameter (CMD) of polydisperse aerosols was about 0.1 µm for NaCl aerosol and 0.3 µm for DEHS.

Three swatch samples were evaluated for each fabric material. A measuring sequence - upstream/downstream/upstream – was repeated 5 times for each swatch. An average of two consecutive upstream readings and in between downstream concentration was used to calculate aerosol penetration.

Experimental system

Aerosol penetration efficiency was measured in an Aerosol Swatch TEst Rig (ASTER) designed according to the ASHRAE 52.2-1999 Standard (ASHRAE 1999). The standard is based on particle counting techniques aimed at determination of total and size dependent aerosol penetration and efficiency through air filters. In this study the standard was modified to allow measurement of aerosol penetration through tested fabric swatch samples. The modification included a scale-down of the original test system and a simplified data analysis method to calculate aerosol penetration. The measuring setup consisted of ASTER (housing swatch samples), an aerosol generation system, sampling lines and aerosol measuring instrumentation.

The ASTER operated in the negative pressure mode. A variable speed air blower drove laboratory air through a HEPA filter delivering it into the main air flow channel. The airflow conditions in the main flow channel were laminar. Test aerosols generated by the aerosol generator were mixed with clean air flowing in the main flow channel. The aerosols were mixed by baffles and passed through the swatch samples placed in a custom designed swatch holder. The pressure drop across swatch samples was measured by a differential pressure sensor (TSI DP-Calc Model 8710). Air velocity, temperature and relative humidity were measured by sensors located downstream of the swatch sample.

The geometry and location of upstream and downstream sampling probes allowed iso-kinetic and iso-axial aerosol sampling (Hinds 1999). The inner diameter (ID) of the main flow channel was 46 mm (surface area of swatch sample ~ 16.6 cm^2); ID for the sampling probes (two identical probes upstream and downstream, thin wall) was 7.6 mm. Aerosols not captured by the swatch sample were filtered by a second HEPA filter placed upstream of the air blower at the end of the main flow channel, passed through the air blower and discharged into a fume hood. The ASTER and sampling lines were made of conductive materials and electrically grounded. The concentration of aerosols (PM$_{10}$ – particle smaller than 10 micrometer) was monitored upstream of the swatch sample using an Optical Photometer (DustTrak, TSI Model 8520).

Aerosol Sampling

The size distribution and concentration of the aerosol challenge were measured upstream and downstream of the swatch sample in a measuring sequence; upstream-purging-downstream. The purging step aimed to eliminate any "memory" effect. The aerosol sampling (airflow direction control, start of sampling) was operated manually. Isokinetic sampling conditions for a given air face velocity (5; 10 and 25 cm.s^{-1}) were achieved by adjusting air flowrates of (i) aerosol instrumentation or (ii) make-up air at the instrument inlets.

A.3.   Fabric filter model

The purpose of the fabric filter model was designed to provide a prediction of the filter behaviour of different fabrics over the full range of face velocities likely to be seen for external wind speeds of up to 10 m.s^{-1}. Filter measurements were taken at specific fabric face velocities (section A.2) to inform the model.

The single fibre model discussed in Section 3.1 is the starting point. This model predicts the filter behaviour based on fabric parameters: fabric thickness and solidity and the diameter of the fibres. The model is well described in the literature (Hinds 1999), so we will not describe it here.

Single fibre theory was originally developed to describe the behaviour of filter type materials rather than fabrics so we don't expect that it will perfectly describe the filter behaviour of fabrics. Two of the parameters of the single fibre model, solidity and fibre diameter, were treated as "effective" rather than real parameters such that the single fibre theory best represented the measured filter behaviour of each fabric over a range of aerosol particle size. The fabric solidity defines the fraction of the fabric volume occupied by the fibres of the fabric (solidity = 1 - porosity).
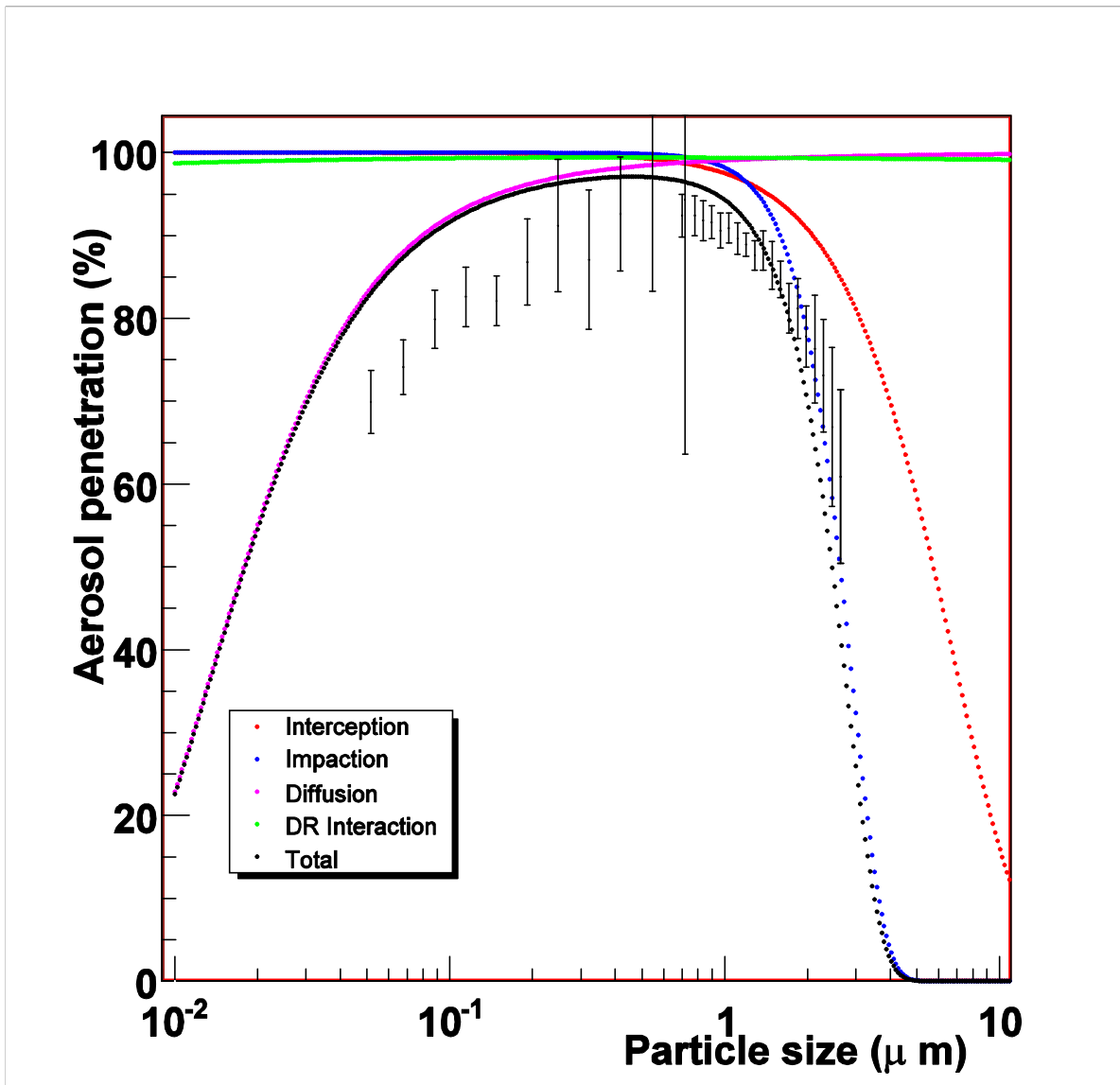
Figure 8: *Filter behaviour of the Black CB suit. The black points with error bars are the measured data. The black points show the best fit single fibre filter model. The coloured points show the contributions from the different filter mechanisms as discussed in section 3.1. The face velocity for this measurement was 10 cm.s^{-1}.*

The results of the fitting are shown in Figure 8 through Figure 11. These figures show the measured filter behaviour of the fabrics. Also shown is the predicted behaviour of the fabric from the single fibre model. The model has been fit by allowing the values of solidity and fibre diameter to vary to minimise the χ^2 difference between the model and the measurements. The possible range of the parameters has been limited, for example the value of solidity cannot go below 0.05. The effective parameter values that give the best fit to the data are different from what we would expect are the real physical values of the parameters. This is expected as these fabrics are made from complex integrated layers, particularly the MkIV and CB Black fabrics.
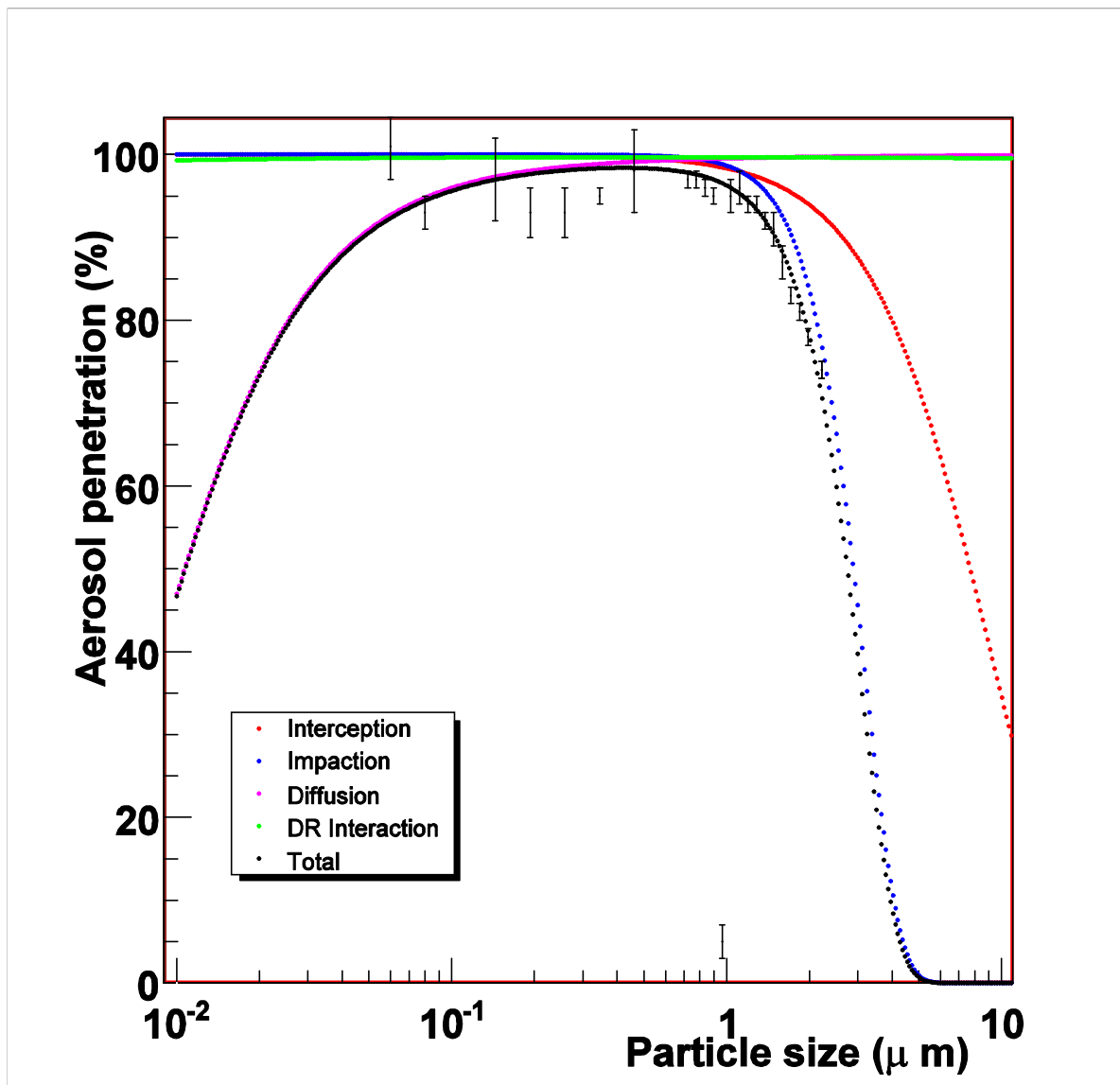
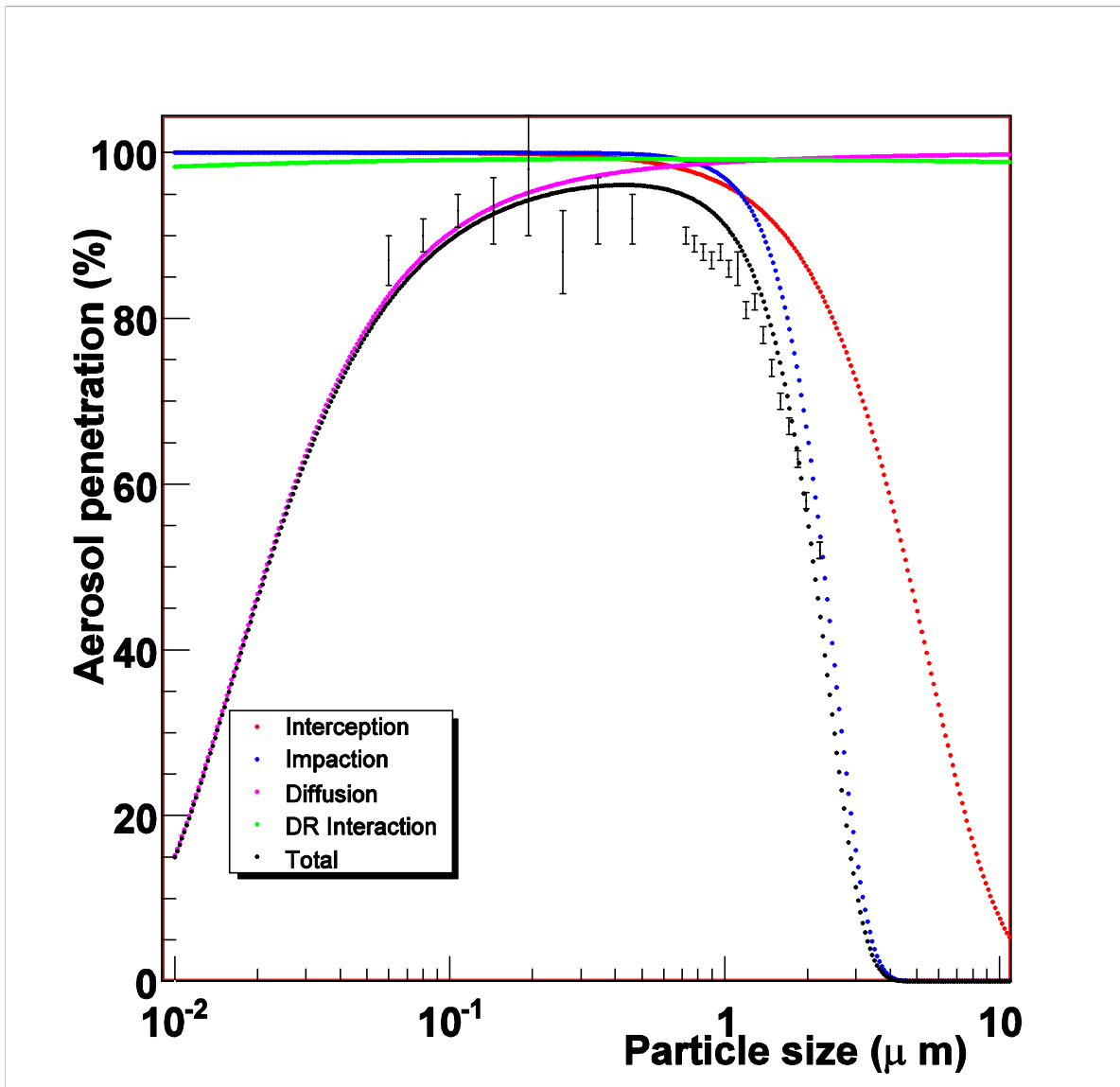*Figure 9:   Same as Figure 8 but for the MkIV outer garment*

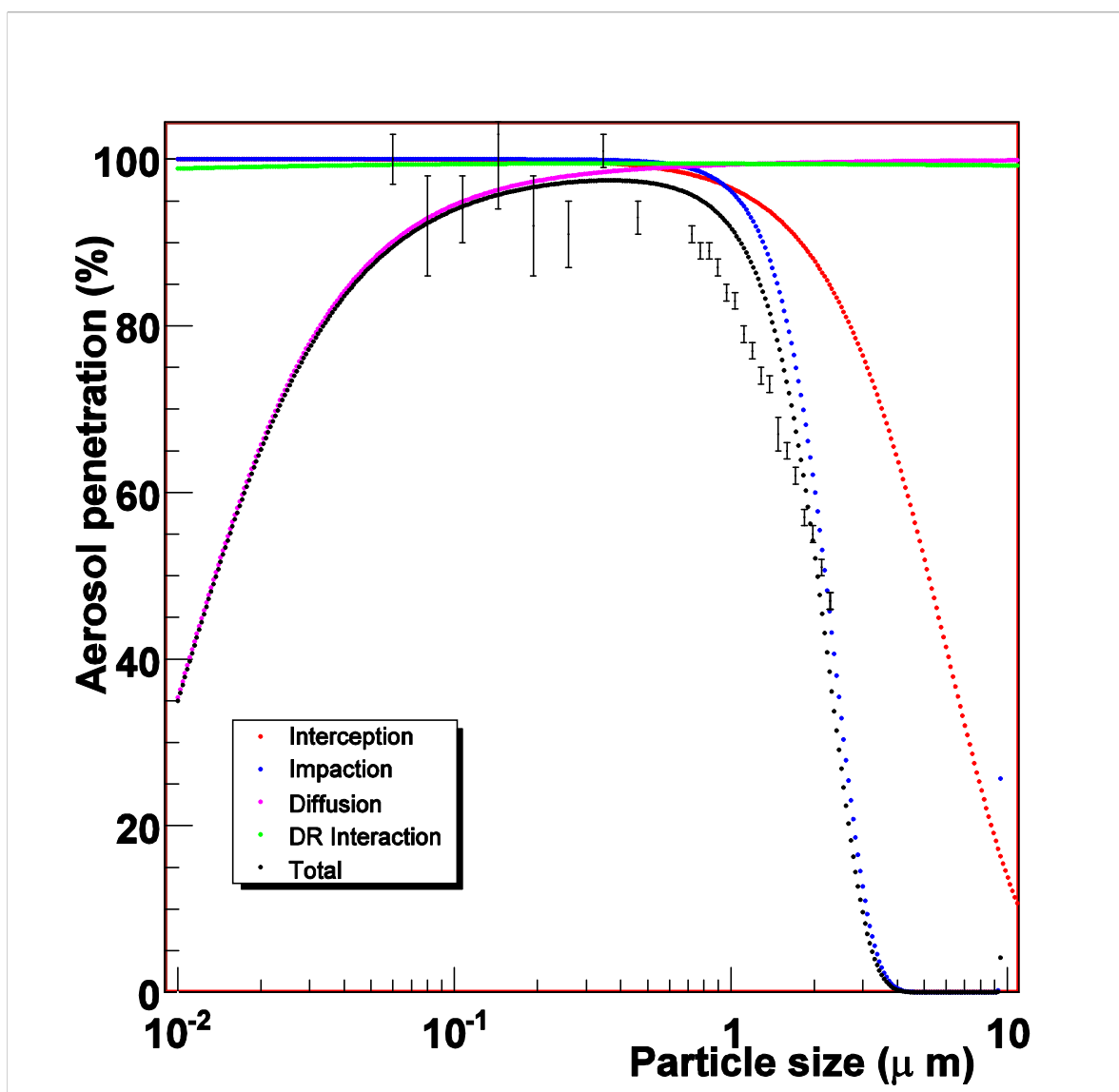*Figure 10: Same as Figure 8 but for the MkIV inner garment*

Figure 11: Same as Figure 8 but for the DPCU Shirt material

Appendix B: Details of the pressure model

The pressure model uses simple cylindrical geometries to represent the shape of the human body and the covering layers of clothing (Figure 2). The pressure and air flow calculations for flow through single layers of fabric follow the work of (Fedele 1992) and (Brasser 2006). The flow of air around a body will cause an external pressure distribution. A Gaussian fit to the pressure distribution for a cylinder in an air flow was used (Stuart 1987). The pressure on the outside of the cylinder, $P_0(\theta)$, as a function of angle around the body, θ, is given by

$$P_0(\theta) = P_S(-1 + 2e^{-2\theta^2}) \quad (\theta \text{ given in radians}) \qquad \text{\textit{Equation 1}}$$

Where hydrostatic pressure $P_2 = \dfrac{1}{2}\rho V^2$ V = wind velocity, ρ = air density

B.1.   Single clothing layer flow model

The flow of air through the layer of clothing is driven by the difference between the outside pressure, $P_0(\theta)$, and the pressure inside the gap , $P_1(\theta)$
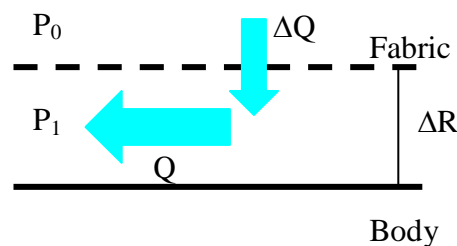

Figure 12: Flow model for one layer of fabric

 Conservation of flow requires that the air volume flowing through the clothing at a given angle, $\Delta Q(\theta)$, be equivalent to the change in volume flow, $Q(\theta)$, in the gap

$$\frac{dQ(\theta)}{d\theta} = R\Gamma(P_0(\theta) - P_1(\theta)) \qquad \text{\textit{Equation 2}}$$

where Γ is the fabric permeability.

Using Poiseuille's law, the resistance to the flow in the gap will induce a pressure gradient around the body inside the gap

$$\frac{dP_1(\theta)}{d\theta} = -\frac{12\mu R^2}{\Delta R^3}Q(\theta)$$

Equation 3

where μ = dynamic viscosity of air, R = radius of the body and ΔR = width of the air gap. Combining *Equation 2* and *Equation 3* gives

$$\frac{d^2P_1(\theta)}{d\theta^2} - \beta^2 P_1(\theta) = -\beta^2 P_0(\theta)$$

Equation 4

where $\beta^2 = \dfrac{12\mu\Gamma R^2}{\Delta R^3}$

Equation 4 can be solved using the external pressure distribution given in *Equation 1* and boundary conditions that result from flow symmetry at the front and back of the body

$$\frac{dP_1(\theta)}{d\theta} = 0; \qquad \theta = 0, \pi$$

An example internal pressure distribution can be seen in Figure 3.

B.2.   Multiple clothing layer flow model

In many practical situations a body would be covered by more than one layer of fabric. The MkIV CBR suit, for example, comprises 2 layers; an outer protective layer and an inner carbon embedded layer. Even a single layer CBR suit such as the Black CB suit could be worn over the top of a T-shirt.

The model developed in Section B.1 can be extended to describe multiple layers of fabric. The simplest approach is to assume that the flows between the layers are not strongly coupled. In this case the presence of the second layer does not strongly affect the pressure and flow conditions in the first layer. *Equation 4* can then be solved for the second fabric layer using the pressure in the first layer as the external pressure distribution. This approach is reasonable if the resistance to flow through the second layer of fabric is significantly higher than the Poiseuille flow resistance through the outer clothing gap. This is the case for the clothing ensembles and gap geometries considered in this report.

A more general solution can be found by considering the coupling of air flow and pressure between the layers of fabric
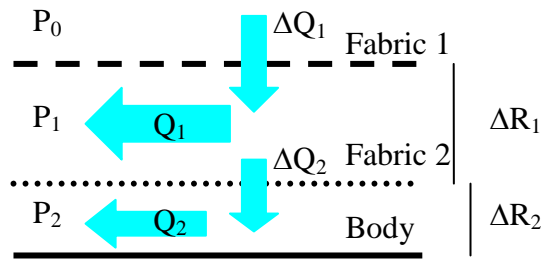
Figure 13: Coupled flow model for 2 layers of fabric

Using the same approach of flow conservation as in *Equation 2* gives

$$\frac{dQ_2(\theta)}{d\theta} = R\Gamma_2(P_1(\theta) - P_2(\theta))$$

$$\frac{dQ_1(\theta)}{d\theta} = R\Gamma_1(P_0(\theta) - P_1(\theta)) - R\Gamma_2(P_1(\theta) - P_2(\theta))$$

leading to a pair of coupled differential equations that could be solved to give the pressure distributions in each of the 2 layers

$$\frac{d^2P_2(\theta)}{d\theta^2} - \beta_2{}^2\Gamma_2 P_2(\theta) = -\beta_2{}^2\Gamma_2 P_1(\theta)$$

$$\frac{d^2P_1(\theta)}{d\theta^2} - \beta_1{}^2(\Gamma_1 + \Gamma_2)P_1(\theta) = -\beta_1{}^2(\Gamma_1 P_0(\theta) - \Gamma_2 P_2(\theta))$$

where

$$\beta_1{}^2 = \frac{12\mu R^2}{\Delta R_1{}^3}, \ \beta_2{}^2 = \frac{12\mu R^2}{\Delta R_2{}^3}$$

and Γ_1 and Γ_2 are the air permeabilities of fabric layers 1 and 2 respectively. The boundary conditions would now become

$$\frac{dP_i(\theta)}{d\theta} = 0; \qquad \theta = 0, \pi$$

This model could be extended to an arbitrary number of fabric layers.

Appendix C: Aerosol deposition model

If the flow in the clothing gaps is laminar then the rate of deposition can be calculated using the parallel plate model (Hinds 1999). The rate of deposition will be determined by the dimensionless parameter μ_d

$$\mu_d = \frac{DLH}{Q\Delta R}$$

where D = particle diffusivity, L = length of travel in gap, H = height of body, Q = volume flow and ΔR = width of the gap.

The deposited fraction δ will depend on the value of μ_d,

$$\delta = 2.96\mu_d{}^{\frac{2}{3}} - 0.4\mu_d \qquad \mu_d < 0.005$$

$$\delta = 1\text{-}0.910\exp\left(\text{-}7.54\mu_d\right) - 0.0531\exp\left(-85.7\mu_d\right) \quad \mu_d \geq 0.005$$

Appendix D: Windows version of the software program

To provide a user friendly interface to the proposed model a special Windows based program was developed to allow an easy input of model configuration parameters. The program provides an easy interface for multiple runs of the model and produces an output in graphical or printable form. This program can be used to estimate the filtration properties of a given fabric or to evaluate the overall performance of a CBRN suit for given properties of the two clothing layers, wind velocity, aerosol properties and body size (see Figure 14, Figure 15).

The main advantage of this program is to give the ability to non-technical users to run and evaluate numerous "what-if" CBR scenarios and to determine an optimal domain of parameters in order to maximise the protective properties of IPE.

The Graphical User Interface (GUI) of the program is written in VB (Visual Basic, V.6). It captures user input, extracts parameter values and calls an internally linked C++ program (described in Section 5) which in turns produces output data files. These data files are read back into the VB program and are displayed by employing the rich graphical capabilities of VB. We hope that this program will provide a useful tool that may assist in test and evaluation or in the acquisition process of IPE by providing a rigorous way of optimising relevant fabric parameter selection.
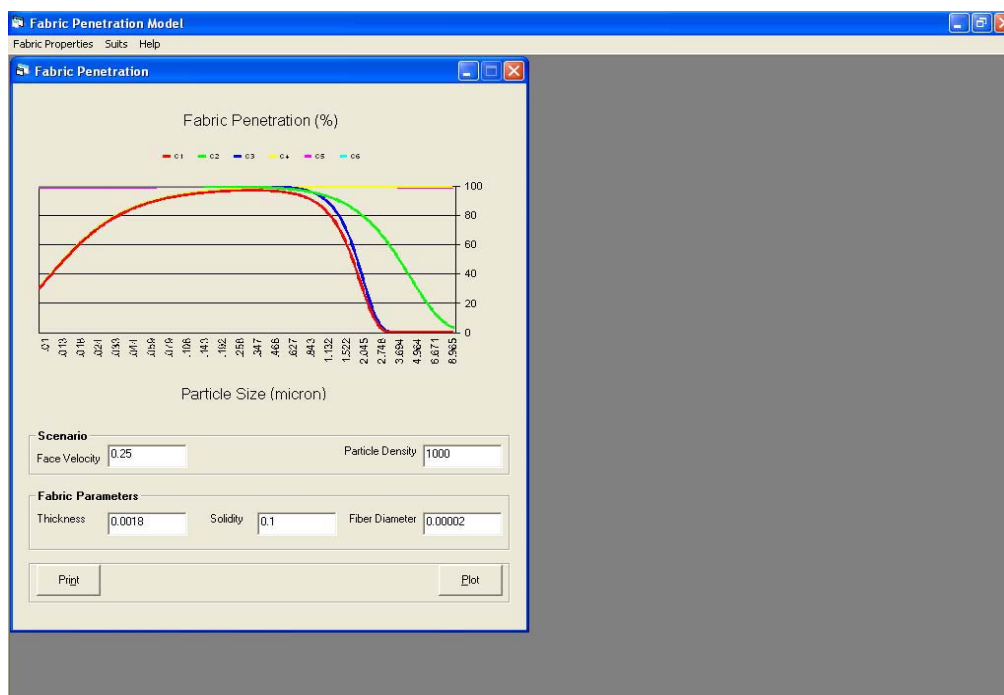

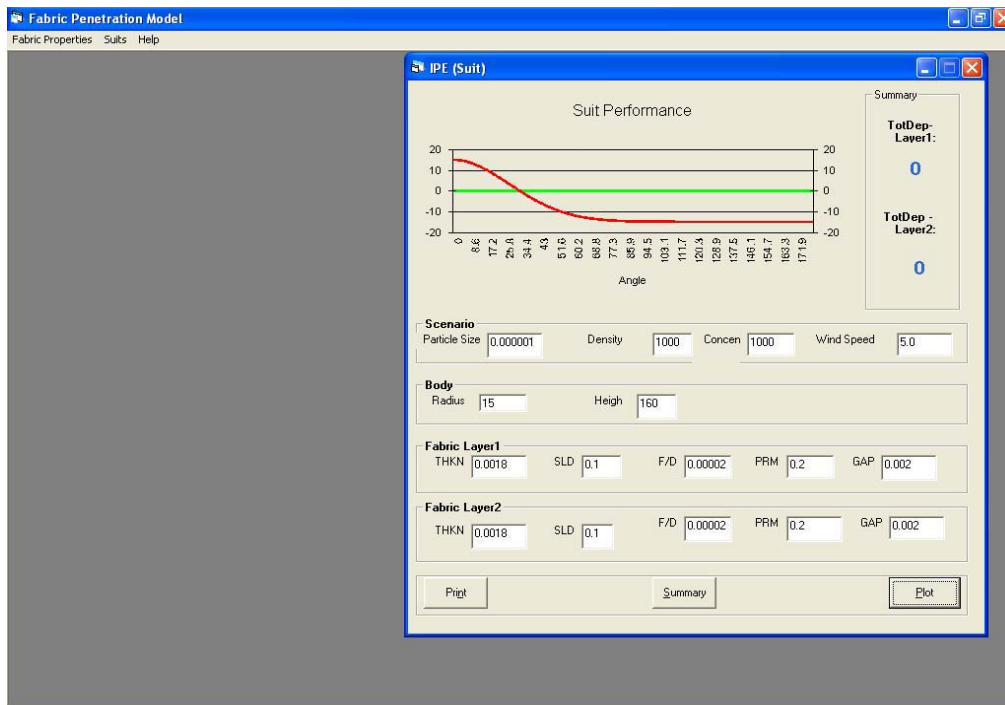*Figure 14: Screen for the evaluation of the protective properties of a fabric*

Figure 15: Screen for the evaluation of the protective properties of a CBRN suit made from two clothing layers

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19. ABSTRACT Aerosol particles can readily penetrate through air permeable fabrics. Air flow and aerosol deposition models were used to determine the skin deposition rates of aerosols through up to two fabric layers. These models were used in conjunction with a plume dispersion model to examine the risks associated with wearing air permeable CBR protective clothing, to inform IPE fabric development programs and allow assessment of aerosol protection requirements.