Optimization of Radio-Opaque Personal Protective Fabric by Monte CarloSimulation

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Summary

The objective of this project was to design and optimize a radio-opaque personal protective fabric to minimize gamma-ray transmittances. For this work,aradioactive particulate transport model was designed to quantify convective leakage of radioactive particulate material(^{137}Cs)into personal protective equipment.A Monte Carlo radiation transport modelwas then used to calculatethe transmittance of a commercially availableradio-opaque combat fabricfor a range of gamma-ray energies. This commercial radio-opaque combat fabric incorporated a thin attenuation layerof tungsten (W). The transmittance values for tungsten and a varietyof other metals were calculated to determine which material minimized gamma-ray transmittance. These materials were then evaluated for their effect on wearer mobility, cost and toxicity. It was determined that anosmium alloy would be the optimal radio-opaque fabric attenuation layer additive.

1. Introduction

Personal protective equipment (PPE) refers to any garment, glove, helmet, boot, or eyewear that is designed to protect the user from various sorts of injury. PPE systems can be worn to protect individuals from blunt force trauma, high-speed impact collisions, electrical hazards, chemical spills, biological threats, exposure to unsafe levels of radiation, or any other health risk.The commercial radio-opaquecombat (CRC)fabric used for this study included a thin attenuation layer of tungsten [1]. The purpose of this work was to determine if a radio-opaque fabric (RF)could be improved, e.g., gamma-ray transmittance reduced, by a substitution of the attenuation layer material. Wearer mobility, cost and toxicity were also evaluated in this process. Transmittance (*T*) is defined as

$$T = \frac{I}{I_0} \quad (1)$$

where I_o is the intensity of mono-energetic gamma-rays that strike the bare detector and I is the intensity of gamma-rays that penetrate through a medium, in this case fabric, and strike the detector [1].

A radioactiveparticle transport model (RPTM) was designed to quantify convective leakage for PPE. This model was used to calculate the mass ofradioactive particle deposition on surfaces and air-gaps within and outside the PPE, based on the surrounding concentration of radioactive particle material (obtained from a NATO scenario of the release of ^{137}Cs in the form ofcaesium chloride(CsCl) [2]).

The Monte Carlo N-Particle Transport Code Version 5 (MCNP-5) was used tosimulateradiationexposure for a forearm sleeve for the radioactive particulate concentrations calculated by the RPTM. TheMCNP model was used to calculate the transmittances of various attenuation layer material additives as a function of gamma-ray energy. A comparison of experimental data obtained from trials with the CRCfabric at the Defence Research and Development Canada - Ottawa were used to validate the MCNP model used for further simulation.

2. MCNP Model

For the MCNP model,the human forearm was represented as a cylinder of 25.6 cm in length and 3.83 cm in radius (average radius for a male human). A distance of 3 cm was selected for the distance between the surface of the forearm and the inner layer of the radio-opaque fabric. This distance represents a typical air gap between the skin and the suit for various personal protective garments. Five radioactive source regions were included in the MCNP model to capture information gathered from the RPTM. These five regions were: (1) on the surface of the forearm (C_{skin}), (2) in the volume between the forearm and inner layer of the suit (C_i), (3) on the inner surface of the suit ($C_{innersuit}$), (4) on the outer surface of the suit ($C_{outersuit}$), and (5) in the volume outside of the suit (C_o).

It was decided to use CRCfabric as the reference case for comparison with the other attenuation material additives because it is desired to find improvements with regards to this commercially available fabric. The inner layer of the CRCfabric was modelled with three layers; a 0.001 cm inner layer, a 0.051 cmmiddle attenuation layer, and a 0.017 cm outer layer [1]. In is important to note that the middle layer contained the attenuation additive (tungsten in the case of the original CRC fabric). The inner and outer layer were structural materials composed of mainly oxygen and carbon and did not contain W [1]. The transmittance of lead(Pb), copper(Cu), iron (Fe),osmium (Os), gold(Au) and platinum(Pt) attenuation additiveswere separately determined by substituting for the mass oftungsten contained in theattenuation layer. All other dimensions and materials were kept identical to the original CRC fabric. For comparison purposes, theRF was modelled with double and half the tungsten content of the initial CRC fabric (denoted Wx2 and Wx0.5, respectively).

The model geometry is illustrated in Figure 1 below.

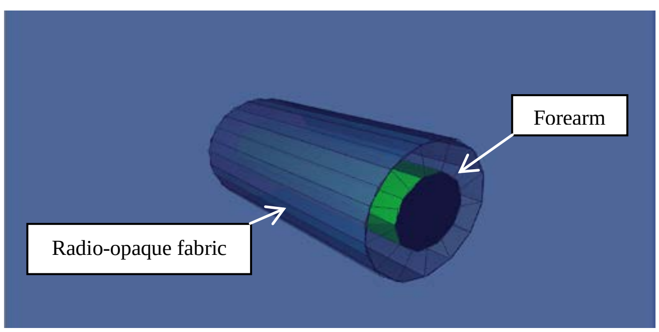

Figure 1: Forearm model geometry. The green cylindrical surface represents the forearm tissue, while the darker blue cylindrical surface represents the layers of radio-opaque fabric. Note that the radio-opaque fabric is modelled in three distinct layers; however, two of them are too small to be seen in the figure.

By combining all of these factors, it was possible to model accurately number of particles incident on the surface of an average male forearm protected by various radio-opaque fabrics during a dispersion event. Transmittance calculations were completed for gamma-ray energies of 100 keV, 200 keV, 300 keV, 661.7 keV, respectively. Note, the 661.7keVemission was included to represent the main gamma-ray emission from ^{137}Cs as CsCl was the radioactive particulate used to obtain the radioactive source terms in the RPTM.

3. Results and Discussion

3.1 Particle Concentration Estimates from Sleeve Ventilation Model

Table 1 provides a summary of the concentrations used to model the CsCldispersion event scenario.

Table 1: Summary of concentration estimates incorporated into MCNP-5 model[2]

Location	Mass Concentrations	Activity Concentrations
C_o	1.67 x 10^{-7} mg cm^{-3}	124Bqcm^{-3}
$C_{outersuit}$	2.55 x 10^{-5} mg cm^{-2}	18900 Bqcm^{-2}
$C_{innersuit}$	1.29 x 10^{-7} mg cm^{-2}	95.5 Bqcm^{-2}
C_i	8.44 x 10^{-10} mg cm^{-3}	0.625 Bqcm^{-3}
C_{skin}	7.60 x 10^{-8} mg cm^{-2}	56.2 Bqcm^{-2}

3.2 Transmittance Optimization

Table 2 provides a summary of the transmittance results generated in MCNP for various photon energies. Table 2 illustrates that the CRC fabric is effective at reducing the transmittances of low energy photons. However, the reduction is less for increasing photon energy. Therefore, 100 keV transmission results will be used for the comparison for the other attenuation material additives (i.e., Pb, Cu, Fe, Os, Au, Pt, Wx2 and Wx0.5).

Table 2: Summary of MCNP-5 generated transmittance results

Radio-opaque FabricAttenuator	Transmittance (Error: ± 0.01)			
	100 keV	200 keV	300 keV	661.7 keV
W (CRC fabric)	0.73	0.98	1.01	1.00
Pb	0.82	-	-	1.01
Cu	0.98	-	-	1.00
Fe	0.99	-	-	1.00
Os	0.67	0.97	1.00	1.01
Au	0.70	0.98	1.01	1.01
Pt	0.67	0.97	1.00	1.01
Wx2	0.21	0.77	0.93	1.01
Wx0.5	0.96	1.01	1.01	1.01

3.3 Engineering Factors Comparison

Table 3 contains a condensed version of the engineering factors resulting from the modeled radio-opaque fabrics. Note: the green denotes an improved condition when compared to the CRC fabric, whereas the red denotes the opposite.

Table 3: Analysis of engineering factors

Radio-Opaque Fabric Attenuator	Transmittance (100 keV)	Cost (US$ kg^{-1})	Density (g cm^{-3}) [7]	Toxic [7]
W (CRC Fabric)	0.73	35.09 [3]	19.26	No
Wx2	0.21	70.18 [3]	38.52	No
Wx0.5	0.96	17.55 [3]	9.63	No
Pb	0.82	2.14 [4]	11.34	Yes
Cu	0.98	8.76 [3]	8.92	No
Fe	0.99	0.79 [5]	7.87	No
Os	0.67	11.82 [6]	22.61	Yes
Au	0.70	55670 [3]	19.32	No
Pt	0.67	53340 [3]	21.45	No

From Table 3, it is evident that lead, copper, and iron-based radio-opaque fabrics can be eliminated, as their respective transmittance values are higher than that of the standard CRCfabric. With respect to the cost, the gold and platinum can be eliminated, as these metals are more expensive than tungsten.

This leaves an osmium-based radio-opaque fabric as the only remaining option. With respect to density, osmium would be only slightly heavier than tungsten for an equivalent volume of material. Thus replacing tungsten with osmium would not result in a significant loss of mobility for the suit's wearer. Unfortunately, it must also be noted that some oxides of osmium are extremely toxic to humans [7]. A solution to this problem would be use an osmium alloy with platinum or iridium as these alloys have been proven to prevent the oxidation of osmium and, subsequently, eliminate its toxic effects. Future analysis is required to evaluate the feasibility of including such alloys in radio-opaque fabrics for cost, transmittance and mobility.

The above table also indicates that, as expected, changing the amount of tungsten, by either doubling or halving, in the CRCfabric has a significant effect on transmittance. This suggests that simply increasing the tungsten content in the attenuation layer could be an effective means of improving the fabric, with respect to transmittance, at the potential detriment of cost and mobility. It remains to be seen, however, if it is even feasible to increase the amount of tungsten in the fabric from a manufacturing point of view.

3. Conclusion and Recommendations

In conclusion, an osmium alloy is suggested as an improved radio-opaque fabric additive with respect to transmittance, cost, user mobility, and toxicity. For future work, it would be necessary to evaluate the feasibility of incorporating such an alloy into a PPE system and how such a change could affect transmittance, cost, and mobility.It is recommended that future studies include beta emitters as potential particulate hazards,as internal suit contamination could result in a significant dose. In order to improve the sophistication of the MCNP model, it is suggested that the MCNP model be expanded to include the entire human body in place of simply a forearm.

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5. References

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