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ADVANCES IN THE SIMULATION OF PERSONAL PROTECTIVE EQUIPMENT FOR THE MITIGATION OF EXPOSURE TO RADIOACTIVE PARTICULATES

M.J. Roeterink[1*], D.G. Kelly[1], E.F.G Dickson[1], and E.C. Corcoran[1]
[1]Royal Military College of Canada, Ontario, Canada
[*]Michael.Roeterink@rmc.ca

Abstract

Airborne radioactive particulates represent a significant potential hazard to first responders in nuclear-related incidents. Personal protective equipment (PPE), in particular radio-opaque fabrics, can be used to reduce wearer exposure to the emitted radiation, but do not offer complete protection. The objective of this project is to create a realistic dosimetric model of the human arm, protected by a sleeve, which can eventually be developed into a tool to assess the full-body dose imparted to the wearer in the event of radiological particulate exposure. A two-fold approach will be employed whereby: (1) a particulate transport model will be used to determine the regional radioactive particulate concentrations; and (2) these concentration data will then be incorporated into a dosimetric model that will use the Monte Carlo N-Particle (MCNP) transport code to determine the dose imparted to the tissue. Benchmarking experiments will be carried out to validate the results generated by the computer models. Such experimentation will be conducted for both the particulate transport and dosimetric models. Model advancement aims to consider whole body dose and will be invaluable in the development of future radiation exposure policies and procedures.

1. Introduction

Throughout history, there have been numerous nuclear-related accidents and incidents. Whilst the cause and consequenceof these events may differ, it is evident that some radiation hazard scenarios occur more frequently than others. In this regard, NATO has identified four radiation hazard scenarios, encompassing each of the main types of radiation, that pose the greatest safety risk to both the general public and emergency personnel [1]. These scenarios are: i) a tactical nuclear weapons strike, ii) the improper disposal of a radioisotope source, iii) the deliberate dispersal of radiological material, and iv) a damaged nuclear reactor facility [1]. Of the four aforementioned radiation hazard scenarios, radiological dispersion events and nuclear reactor events represent the greatest health threat to military members and first responders as they often result in the release of very high concentrations of airborne radioactive particulates near ground level [1]. Airborne radioactive particulates are one of the most significant hazards facing emergency personnel during a nuclear incident and, as such, must be taken into consideration when attempting to predict human exposure levels.

In order to help protect people from the harmful effects of radiation, the International Commission on Radiological Protection (ICRP) publishes strict guidelines outlining the acceptable exposure limits for nuclear energy workers (NEW) and the general population. To allow human radiation exposure to be evaluated in a quantitative manner, the ICRP defines absorbed dose, D, as the quotient of the mean energy transferred by ionizing radiation to a volume of matter, $d\bar{\varepsilon}$,per unit mass of irradiated material, dm, making up that volume, Equation 1 [2].

$$D = \frac{d\bar{\varepsilon}}{dm} \quad (1)$$

According to the ICRP 60 Recommendations, NEWs may receive a dose of 100 mSv over five years, with a maximum dose of 50 mSv in any one year being deemed acceptable [3]. Not surprisingly, there are much more stringent acceptable exposure limits for the general public; moreover, it is advised that these individuals receive only a dose of 1 mSv per year above that normally contributed by naturally-occurring background radiation [3]. NATO has also issued its own series of guidelines identifying Radiation Exposure State (RES) categories and the corresponding acceptable exposure limits for military personnel [4]. As presented inTable 1, military members are allowed to receive a certain cumulative dose based on the RES category assigned to theincident in question [4]. It should be noted that the cumulative doses listed inTable 1correspond to the acceptable dose limit that can be received in response to a single event and not a given time period.

Table 1: RES categories and corresponding acceptable dose limits

RES Category	Total Cumulative Dose (mSv)
0	0 – 0.5
1A	0.5 -5
1B	5 – 50
1C	50 – 100
1D	100 – 250
1E	250 – 750

In order to help meet these recommendations, traditional radiation safety theory advocates adhering to the "As Low As Reasonably Achievable (ALARA)" mentality [5]. ALARA relies on the principles of time, distance, and shielding to minimize radiation exposure [5]. In this regard, ALARA aims to reduce contact with the radiation source by decreasing the amount of time spent in its vicinity, maximizing separation distance, and utilizing relevant shielding materials wherever and whenever possible.It is difficult to apply ALARA to many radiation hazard scenarios as the dynamic and undefined nature of these events may require emergency personnel to work for prolonged periods of time in close proximity to a radiation source. Additionally, traditional shielding mechanisms have a high physiological burden associated with their use and are often too cumbersome to be carried for protection. However, radio-opaque fabrics are marketedwith the ability to reduce personnel exposure to radiation hazards by attenuating incident radiation and providing isolation from radioactive particulates. Whilst it has been reported that a single layer of these fabrics can attenuate up to 50 % of incident gamma photons with an energy below 130 keV[6], further work is required to assess the effectiveness of radio-opaquepersonal protective fabricsunder different radiological conditions and to investigate the transport of radioactive particles through closures when these air non-permeable materials are incorporated into suits or through other types of air permeable protective fabrics.

2. Project objective

The objective of this project is to create a realistic dosimetric model of the human arm, protected by a sleeve, which can eventually be developed into a tool to assess the full-body dose received by the wearer in the event of radiological particulate exposure. A two-fold modelling approach will be employed whereby: (1) a particulate transport model will be used to determine the concentration of radioactive particulatesin the regions surrounding the forearm (both within and outside the protective suit); and (2) these concentration data will then be incorporated into a dosimetric model that will use the Monte Carlo N-Particle Transport Code, Version 5 (MCNP5) to determine the dose imparted to the

tissue. It has been decided to model a human forearm and sleeve in place of an entire human phantom as this will significantly simplify the model geometry and be less computationally intensive.Also, it has been decided to limit the type of radioactive particulates to those that emit beta particles and gamma photons. The reasoning behind narrowing the particulate selection is that alpha particles have a well-defined range in air and pose less hazard as an external dose and it has be shown that neutrons are not attenuated by current radio-opaque personal protective fabrics [7].Experimentation will be carried out to benchmark the results generated by both the particulate transport and dosimetric computer models. Future model advancement aims to consider whole body dose, which will be invaluable in the development of future radiation exposure policies and allow for comparison with the recommended exposure guidelines.

3. 'Forearm' model

3.1 Particulate transport model

Particulate diameter and concentration are the two most important parameters when modellingparticulate transport through closures or fabrics andthis information, combined with the type of radioisotope,is of primary importance when determining health effects from radiation [8]. With this in mind, there are two distinct modes by which airborne particulates move from one location to another: convective mass transfer and diffusion [9]. Convective mass transfer is the dominant transport phenomenon in regions far from a phase interface and is heavily influenced by convective fluid flow [9]. Contrastingly, diffusion occurs when a concentration gradient gives rise to a net movement of species from a location of high concentration to that of lower concentration and is most noticeable very close to the phase interface [9]. Ultimately, this concept is the driving force behind Fick's first law of diffusion.

As presented in Equation 2, Fick's first law of diffusion states that the diffusive flux of some species, J_A, is proportional to the diffusion coefficient, *D*, and the concentration gradient of that species, $\frac{dc_A}{dx}$ [10].

$$J_A = -D\frac{dc_A}{dx} \quad (2)$$

Unfortunately, Fick's first law is only applicable to steady state diffusion; moreover, because the present work seeks to investigate how the concentration of radioactive particulates surrounding the forearm varies with time, it is necessary to use Fick's second law of diffusion. The generic version of Fick's second law states that the rate of change of the concentration, $\frac{dc_A}{dt}$, is proportional to the diffusion coefficient, *D*, and the rate of change of the concentration gradient, $\nabla^2 c_A$[10]. To better represent the actual physical transport of the airborne radioactive particulates, it is necessary to include an additional term to account for the effects of convection, $v^* \cdot \nabla c_A$. Equation 3 illustrates the updated expression for Fick's second law of diffusion that will be used in this work.

$$\frac{dc_A}{dt} + v^* \cdot \nabla c_A = D\nabla^2 c_A \quad (3)$$

At the initial time,t_0,during a radiation hazard scenario, emergency personnel will experience a concentration of radioactive particulates in the air outside of theirprotective suit and on the surface of the suit itself. These two regional concentration values will be known as c_o and $c_{outersuit}$ respectively

and are shown in Figure 1a.The surface concentrations are in units of aerial deposition, specifically mg cm^{-2}. If the suit is air permeable, over time, these particulates will diffuse through the fabric at a rate that is proportional to the diffusion coefficient and the rate of change of the concentration gradient. Additionally, forair non-permeable fabrics, diffusion can also occur through improperly sealed closuresor fabrictears. As result,after a long time, t_∞, there will now be a concentration of radioactive particulates on the inner surface of the suit, in the air gap between the wearer's arm and the suit, and on the surface of the arm. These regional concentration values will be known as $c_{innersuit}$,c_i, and c_{skin} respectively and have been included for reference in Figure 1b.

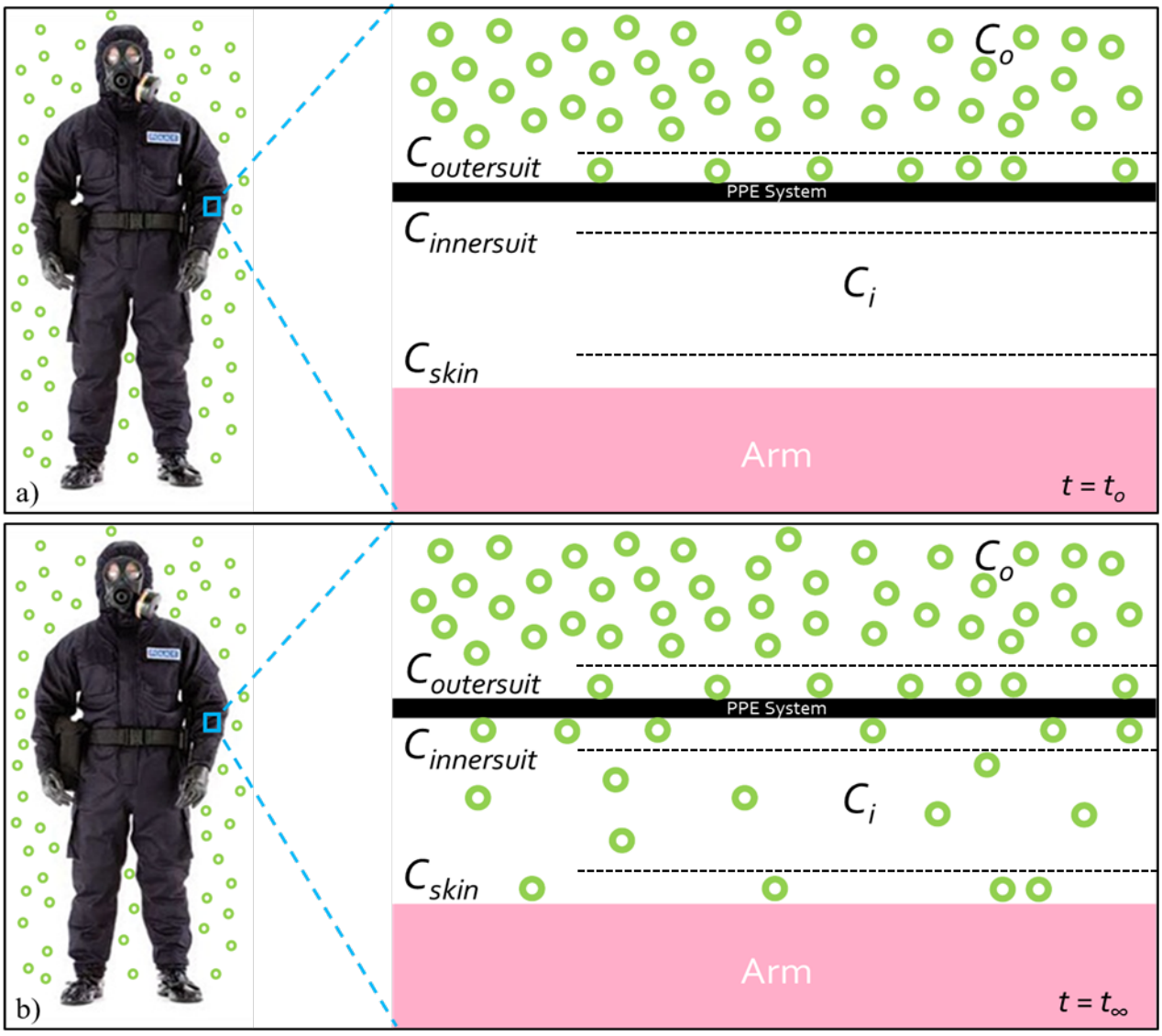

Figure 1: Regional concentration profile at t_0 and t_∞ for an air permeable fabric

In order to determine each of the five regional radioactive particulate concentration values (e.g.,c_o, $c_{outersuit}$, $c_{innersuit}$,c_i, and c_{skin}), the system will be modelled using theCOMSOL Multiphysicssoftware package. COMSOL is a finite element analysis solver that uses the Galerkin method to numerically solve differential equations and allows users to couple various physical phenomena with complex geometric designs of realistic environments [11]. Thus, by specifying various parameters such as the particulate diameter, deposition velocity, diffusion coefficient of the fabric, and convective flow rate, it

will be possible to create a COMSOL model that can solve Equation 3 at each of the five regions surrounding the arm. In this regard, it will be possible to determine the five regional radioactive particulate concentration values for a static arm, protected by an air non-permeable or air permeable fabric,with or without an improperly sealed closure, as a function of time. A preliminary version of the COMSOL-based particulate transport model is presented in Figure 2.

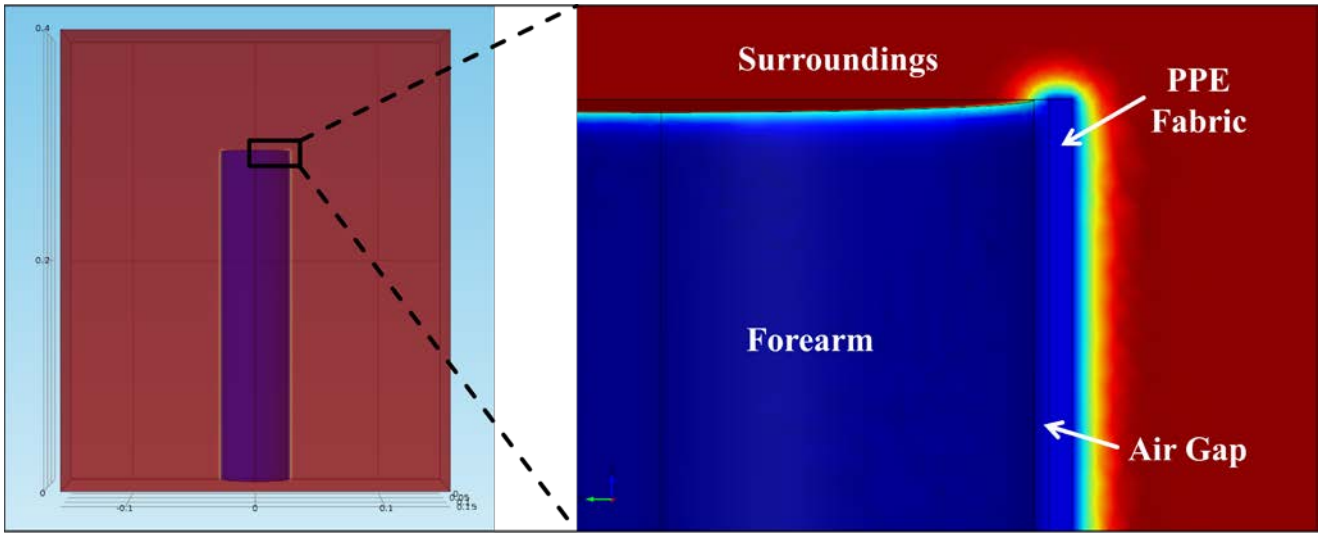

Figure 2: Preliminary particulate transport model developed using the COMSOL Multiphysics software (red and blue areas represent regions of high and low concentration respectively)

3.2 Dosimetric model

The dosimetric model will be implemented using the MCNP5 software. MCNP5 was developed by the Los Alamos National Laboratory (LANL) and is the internationally recognized simulation code for analysing the transport of gamma photons, electrons, and neutrons using the Monte Carlo method [12]. It is a stochastic computer code that allows the user to generate detailed replicas of realistic environments; moreover, using a random number generator and physical cross section data, MCNP5 is able to determine the likelihood that a species undergoes a nuclear event while traversing through saidgeometries [12]. Additionally, the code can be used to simulate the production of different types of secondary radiation, such as the emission of delta rays, Auger electrons, characteristic X-rays, and bremsstrahlung photons, that are produced as a consequence of interactions between source particles and the environmental geometry [12]. Finally, by running a large number of particles, MCNP5 is able to provide the user with the most probable outcome per source particle and an associated uncertainty.

In the present work, MCNP5 will be used to calculate the dose that is imparted to a given volume of forearm tissue, both in the presence and absence of a radio-opaque protective fabric,for a variety of radiation hazard scenarios. In this regard, it was first necessary to construct the model geometry with the corresponding materials composing each component. As pictured in Figure 3, for the dosimetric model, cylinders of various dimensions are used to represent the forearm and radio-opaque protective fabric. The inner cylinder is composed of tissue, whilst the outer is modelled so as to mimic the elemental composition, density, and thickness of the protective fabric being assessed. A rectangular prism, filled with air, is used to simulate the external environment surrounding the protected forearm. The next area of interest is modelling the radiation source. To this extent, using the MCNP5 software, the user can manipulate a number of different factors to ensure that the source is properly defined; moreover, it is possible to vary the location of the source, its dimensions, as well as the type, direction,

and energy of the particles being emitted [12]. Each of these parameters will differ in accordance with the radiation hazard scenario that is being modelled and the results of the particulate transport model. Finally, in order to determine the dose that is imparted to the forearm tissue an energy deposition tally (f6) will be employed. For this type of tally, MCNP5 sums the total amount of energy deposited in a volume, as a result of nuclear interactions and averages it per source particle [12].In this manner, the MCNP5 software can be used determine the dose that is imparted to the forearm tissue.

3.3 Determining the dose imparted to the 'forearm' tissue in the event of radiological particulate exposure

In order to determine the dose that is imparted to the human forearm in the event of radiological particulate exposure, the five regional radioactive particulate concentration values (c_o, c_i, $c_{outersuit}$, $c_{innersuit}$, and c_{arm}) from the particulate transport model will be incorporated into the dosimetric model. In this regard, these five regional concentration values will become the source terms used for the MCNP5 simulations, Figure 3. Treating the source terms as such will allow for a more realistic calculation of the dose that is imparted to the forearm tissue, covered by a radio-opaque protective fabric, during a radiation hazard scenario involving the release of airborne radioactive particulates. Additional simulations will be completed to determine the dose received by the forearm tissue in the absence of any protective fabrics. Thus, it will be possible to determine the impact that the presence of a PPE fabric has on the dose imparted to the human forearm.

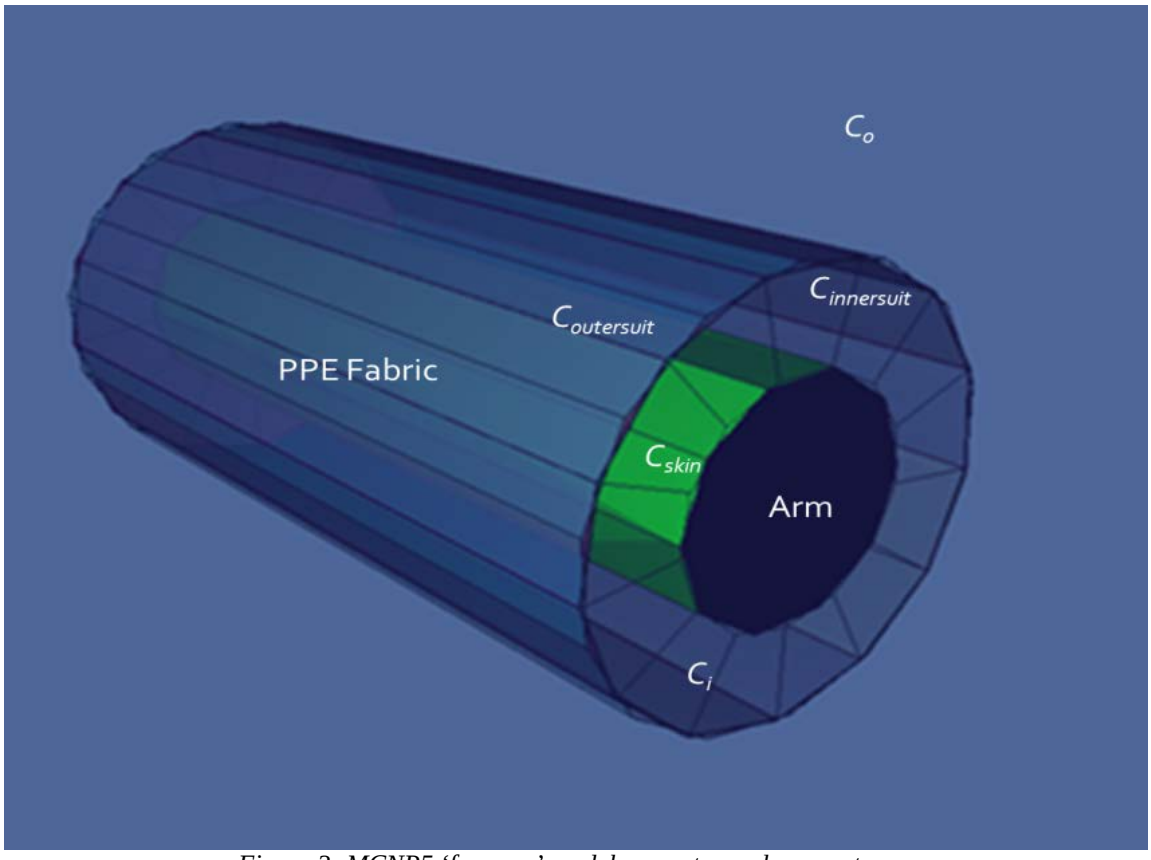

Figure 3: MCNP5 'forearm' model geometry and source terms

4. Benchmarking experimentation

Because the present work is heavily rooted in computer simulation, it is necessary to conduct benchmarking experiments for the purpose of validating both the particulate transport and dosimetric models. The focus of these experiments is to illustrate that the COMSOL Multiphysics and MCNP5 software can be used to accurately replicate real-world phenomena by comparing the respective model outputs with the experimentally-obtained results.

4.1 Particulate transport modelbenchmarking

The particulate transport benchmarking experimentation is being conducted in conjunction with the Royal Military College of Canada (RMCC) CBRN Protection Group. The aim of this experiment is to measure the concentration of a surrogate particulate species, as a function of time, inside and outside of a phantom forearm apparatus. The forearm apparatus, shown in Figure 4, consists of a solid aluminum rod, representing the forearm, surrounded by anouter aluminum cylinder, designed to simulate an air non-permeable fabric. The resulting inner volume is seperated into six channels that are oriented in the axial direction. The end cap has been designed such that slots can be remotely opened or closed to allow or deny particulates access to the inner volume of the cylinder. Sampling occurs at the opposite end of the cylinder.Before beginning the experiment, the inner volume of the cylinder is evacuated to ensure a zero concentration of particulates.The apparatus is then sealed and placed inside a large box. A condensation monodisperse aerosol generator is used to pump surrogate particulates into the box. The surrogate particulates are oil-based and generated so as to be representative of the actual airborne radioactive particulates in terms of aerodynamic diameter (~ 2.3 μm). For health and safety reasons, the surrogate particulates used in the experiment are not radioactive. Two aerodynamic particle sizer (APS) spectrometers are arranged such that one of them is able to record the concentration of surrogate particulates inside the forearm apparatus, whilst the other measures the concentration within the confines of the box. Once a stable outer concentration is reached, the end cap is opened which allows the external surrogate particulates to enter the previously clean forearm apparatus. In this respect, it is possible to measure the concentration of surrogate particulates inside and outside of the forearm apparatus as a function of time after a ‘leak’ in the closure occurs. The APS spectrometers are of additonal benefit as they are able to separate the sampled particulates into distinct size bins according to their aerodynamic diameter at each sampling interval. Thus, a wide range of data can be collected during a single experimental trial.

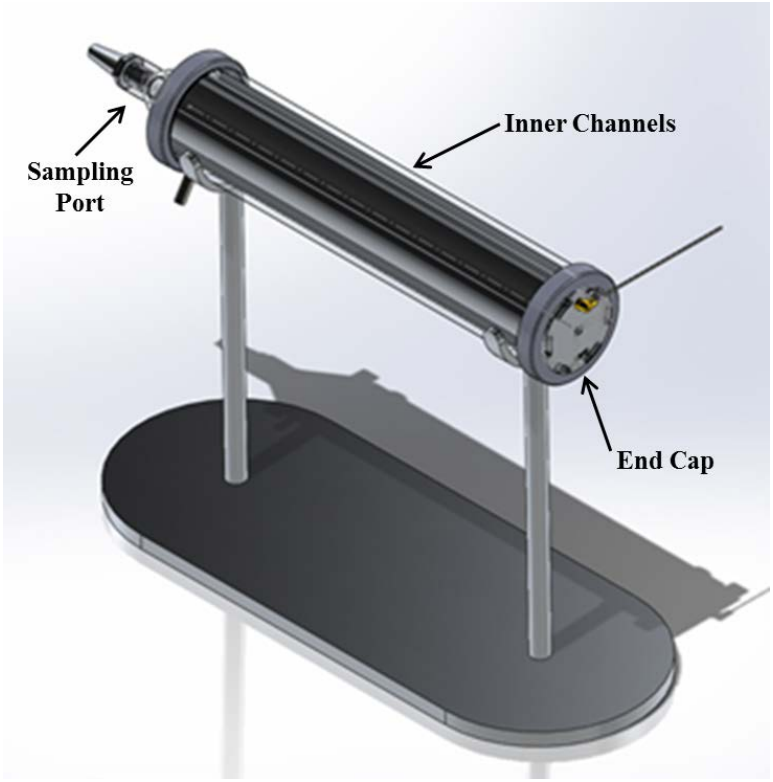

Figure 4: Phantom forearm apparatus used for the particulate transport benchmarking experimentation

Once this experimental data collection is completed, the next step is to develop the corresponding COMSOL model. In this respect, the experimental geometry will be recreated to a high level of detail, whilst the built-in "Transport of Diluted Species" package will be used to simulate the diffusive and convective phenomena affecting the transport of the particulates. The aim of the COMSOL model is to replicate the experimentally-obtained concentration values both inside and outside of the forearm apparatus and, hence, benchmark the software for use in this work.

4.2 Dosimetric modelbenchmarking

The dosimetric model benchmarking was completed with the assistance of the RMCC Analytical Science Group (ASG) as discussed in Reference 13.The objectives of this experiment were to characterize and measure the gamma photon attenuation capabilities of a second generation CRC fabric and use these results to benchmark the MCNP5 code. Thus, through experimentation, the reduction in transmittance of a multi-radionuclide challenge source by a single layer of the second generation CRC fabric and a fabric-free reference was tested using one hour exposures with real-time gamma photon detection. In order to benchmark the MCNP5 software against the transmittance experimentation, it was first necessary to model the geometry of the experimental set-up to a high degree of accuracy. In this regard, the design specifications for the high purity germanium detector were referenced from the manufacturer; moreover, this included information pertaining to the dimensions, density, and elemental composition of each of the components of the detector. Additionally, detailed geometric measurements of the acrylic holder, protective lead castle, and multi-radionuclide challenge source were made.The certificate of calibration, provided with the challenge source, was referenced to ensure the source activities included in the MCNP5 model were consistent with those of the experimentation. Finally, the elemental composition and density of the second generation CRC fabric were modelled based on characterization test results. The MCNP5 model geometry used to simulate the transmittance

experimentation is shown in Figure 5. Once the experimental geometry had been successfully modelled, a pulse height (f8) tally was employed to count the number of pulses within the detector volume in the presence and absence of the second generation CRC fabric. Discrete energy bins were included in the model such that the energy of the incident gamma photons could be determined. This allowed for the transmittance of a single layer of the fabric to be calculated at each of the energies corresponding to the radionuclides of the challenge source.

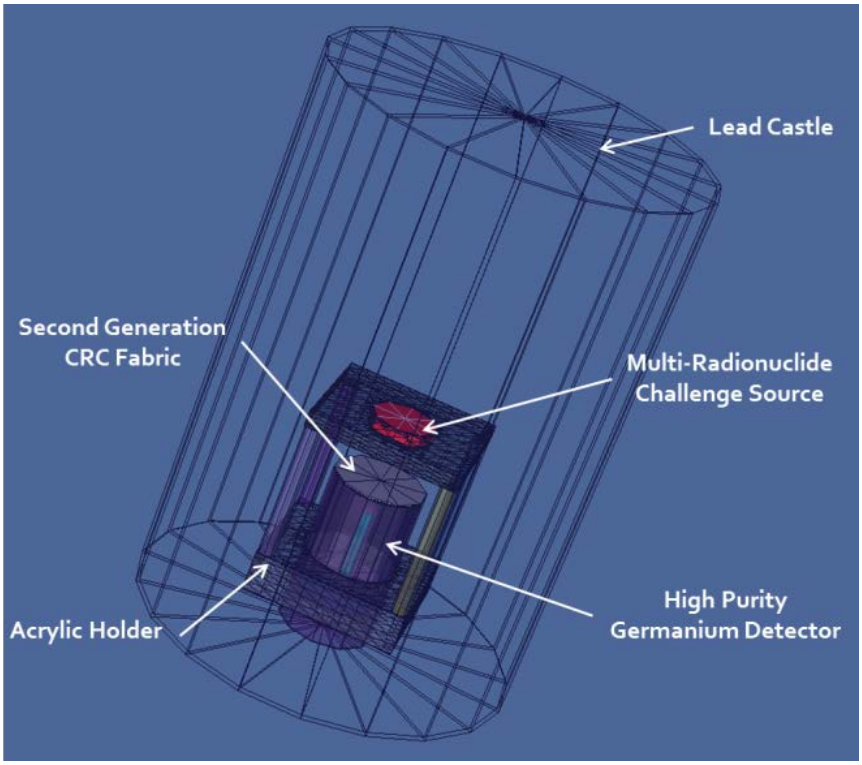

Figure 5: MCNP5 model geometry used to simulate transmittance experimentation

For the initial MCNP5 model, with the exception of a single region between 50-80 keV, the experimental and MCNP5 transmittance results closely aligned for the range of gamma photon energies investigated. Experimentally, the region of discrepancy corresponded to a single experimental datum point at 59.5 keV were the MCNP5 model drastically over-predicted the observed experimental transmittance at this energy. In order to explain this discrepancy, it was necessary to gain more insight regarding the energies of the gamma photons incident on the detector, both experimentally and in the MCNP5 model. As such, a refined MCNP5 model was developed in which the energy bins used to catalogue the incident gamma photons were reduced to 0.1 keV increments. The results from the refined model indicated that, within the region of discrepancy, the majority of the photons incident on the detector possess energies of either 58.2 keV or 59.5 keV. The former energy is characteristic of the secondary X-rays released as a result of transitions between the L- and K- electron orbital shells in tungsten, whilst the later corresponds to the photons that are emitted directly by ^{241}Am in the multi-radionuclide challenge source [14]. Upon comparing the results of the refined MCNP5 model with the experimentally-obtained spectrum, it was identified that the computer software used to perform the experimental analysis integrated under the peak corresponding to the ^{241}Am challenge radionuclide and excluded the counts generated by the secondary X-rays. This exclusion explained why the MCNP5 model over predicted the experimentally-obtained results; furthermore, it was possible to determine what percentage of the overall transmittance stemmed from the secondary X-rays by dividing the

number of particles incident on the detector having an energy of 58.2 keV by the total number of particles incident on the detector. Using this ratio, the initial MCNP5 transmittance value at 59.5 keV was adjusted in order to account for the exclusion of the counts generated by the secondary X-rays. This resulted in an improved MCNP5 model that is fully consistent with the experimentally-obtained transmittance results, given each of their respective uncertainties, Figure 6.

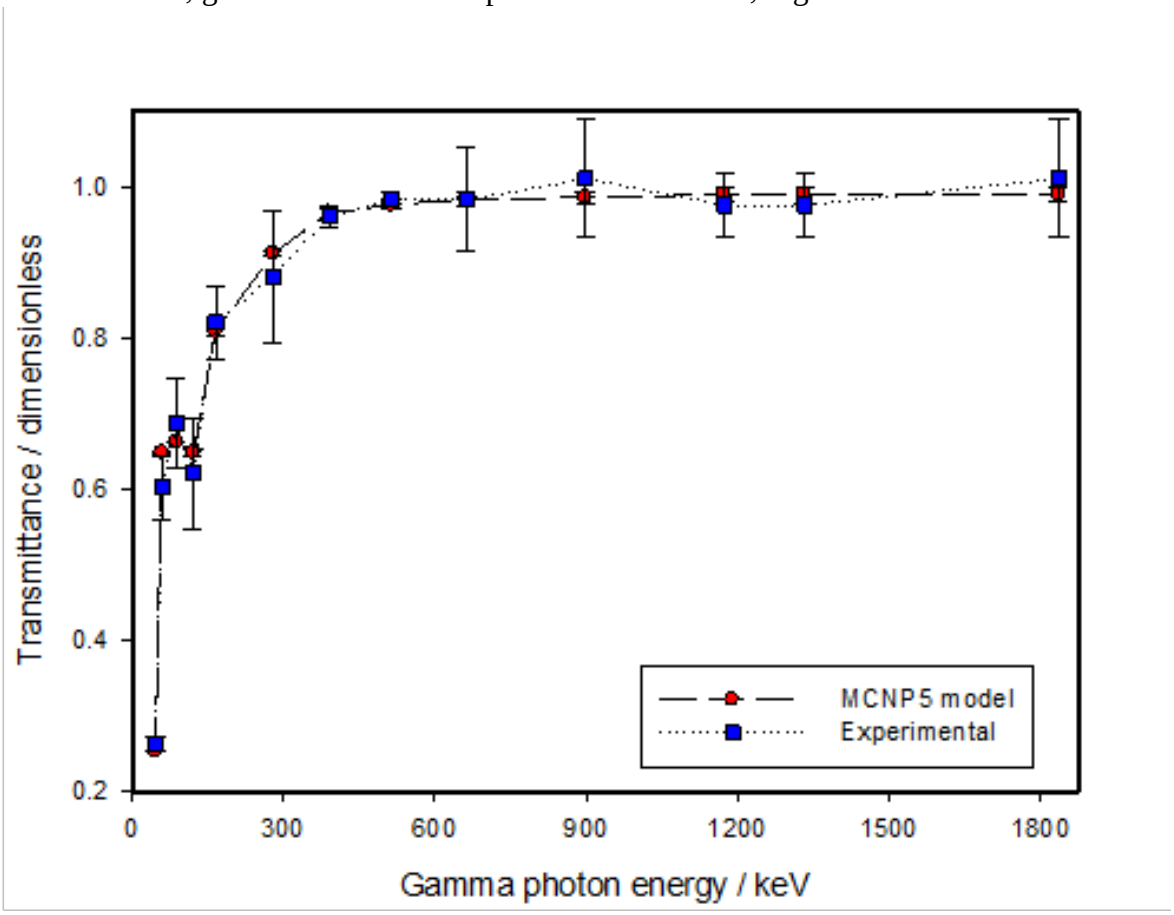

Figure 6: Experimental andMCNP5 transmittance results for a single layer of the second generation CRC fabric [13]

5. Preliminary Results from the Combined Transport and Dosimetry Models

A preliminary MCNP5-based dosimetric model has been generated using estimates acquired from the literature for the five regional radioactive particulate concentration values. The concentration estimates were the obtained from a NATO test scenario simulating the detonation of a radiological dispersion device(RDD) containing caesium chloride [1]. For the preliminary model, two different scenarios were simulated. The first scenario was directly related to the NATO test and involved the release of the radionuclide caesium-137, which emits gamma photons withan energy of 661.67 keV.The second was based on the hypothetical release of airborne radioactive particulates emitting 100 keV gamma photons. For both scenarios, simulations were performed to determine the dose imparted to the forearm tissue in both the presence and absence of first and second generation CRC fabrics. Only gamma radiation was considered for the preliminary model.

As shown in Table 2, neither the first nor second-generation CRC fabrics were effective at attenuating the higher energy gamma photons.As a result, the dose imparted to the forearm tissue was effectively equivalent regardless of the presence or absence of a protective fabric. Conversely, for the scenario involving the hypothetical 100 keV gamma photons, statistically significant reductions in the dose

received by the forearm tissue were identified for both the first and second generation CRC fabrics relative to the no shielding alternative (30 to 40 %, respectively). This indicates, as expected from pervious results,that the PPE materials may be able to offer increased protection capabilities for lower energy photon incidents [7, 13]. Future model development will include the five regional concentration values from the particulate transport model as source terms in the dosimetric model, as well as the inclusion of beta radiation considerations.

Table 2: Analysis of dose rate imparted to forearm under various radiological and shielding conditions

Incident Photon Energy / keV	Shielding	Dose Rate / mSv hr^{-1}	Reduction of Intensity / %
661.67	No Shielding	0.239 ± 0.003	-
	First Generation CRC fabric	0.237 ± 0.003	<1.0
	Second Generation CRC fabric	0.237 ± 0.003	< 1.0
100	No Shielding	0.0289 ± 0.0003	-
	First Generation CRC fabric	0.0203 ± 0.0003	30
	Second Generation CRC fabric	0.0167 ± 0.0002	40

6. Summary

A preliminary MCNP dosimetric model has been successfully developed for radiation hazard scenarios involving radionuclides emitting gamma photons. The particulate transport model is still under development; however, upon completion, it will be possible to determine the five regional radioactive particulate concentration values and incorporate them into the dosimetric model. The dosimetric model has been successfully benchmarked against experimental data. For the particulate transport model benchmarking,the process of gathering the experimental data is underway.

7. Acknowledgements

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