Advances in the Simulation of Personal Protective Equipment for the Mitigation of Exposure to Radioactive Particulates

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Summary

Personal protective equipment (PPE), in particular radio-opaque fabrics, can be used to reduce wearer exposure to airborne radioactive particulates, 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 confirm the results generated by each computer model.

1. Introduction

Throughout history, there have been numerous nuclear-related accidents and incidents. Whilst the cause and consequence of 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]. Of the four scenarios, radiological dispersion events and nuclear reactor events represent the greatest health threat to emergency personnel 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. 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, whilst it is advised that the general public receive only a dose of 1 mSv per year above that contributed by naturally-occurring background radiation [2].

In order to help meet these recommendations, traditional radiation safety theory advocates adhering to the "As Low As Reasonably Achievable (ALARA)" mentality [3]. 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. Fortunately, radio-opaque fabrics are marketed with the ability to reduce personnel exposure to radiation hazards by attenuating incident radiation and providing isolation from radioactive particulates; however, further work is required to assess the effectiveness of these fabrics under varying radiological conditions and to investigate the transport of radioactive particulates through them.

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 particulates in different regions surrounding the forearm; 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 as alpha particles pose less hazard as an external dose due to their well-defined range in air and neutrons are not attenuated by current radio-opaque personal protective fabrics [4]. Experimentation will be carried out to benchmark the results generated by both the particulate transport and dosimetric computer models.

3. ‘Forearm’ model

3.1 Particulate transport model

The present work uses Fick’s second law of diffusion to investigate how the concentration of radioactive particulates surrounding the forearm varies with time. 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, $\nabla^2 c_A$ [5]. 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 1 illustrates the expression for Fick’s second law with the inclusion of the convective term.

$$\frac{dc_A}{dt} + v^* \cdot \nabla c_A = D\nabla^2 c_A \tag{1}$$

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 their protective suit and on the surface of the suit itself. These two regional concentration values will be known as c_o and $c_{outersuit}$ respectively. 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, for air non-permeable fabrics, diffusion can also occur through improperly sealed closures or fabric tears. As result, after an extended period of 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. The COMSOL Multiphysics software model will be used to solve Equation 1 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 (c_o, $c_{outersuit}$, $c_{innersuit}$, c_i, and c_{skin}) for a static arm, protected by an improperly sealed, air non-permeable fabric or air permeable fabric as a function of time.

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 [6]. 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. This is accomplished by first constructing the model geometry with the corresponding materials comprising each component. Next, the five regional radioactive particulate concentration values (c_o, c_i, $c_{outersuit}$, $c_{innersuit}$, and c_{arm}), obtained from the particulate transport model, will be incorporated as source terms into the dosimetric model, Figure 1. By using five independent source terms, it will be possible to distinguish between the dose imparted to the forearm by the external radioactive particulates and that which is contributed by the radioactive particulates within the confines of the suit fabric. Furthermore, this will allow for a more realistic calculation of the dose that is imparted to the forearm tissue during a radiation hazard scenario involving the release of airborne radioactive particulates emitting gamma and beta radiation. 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 [6]. Additional simulations will be completed to determine the dose received by the forearm tissue in the absence of any protective fabric. 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.

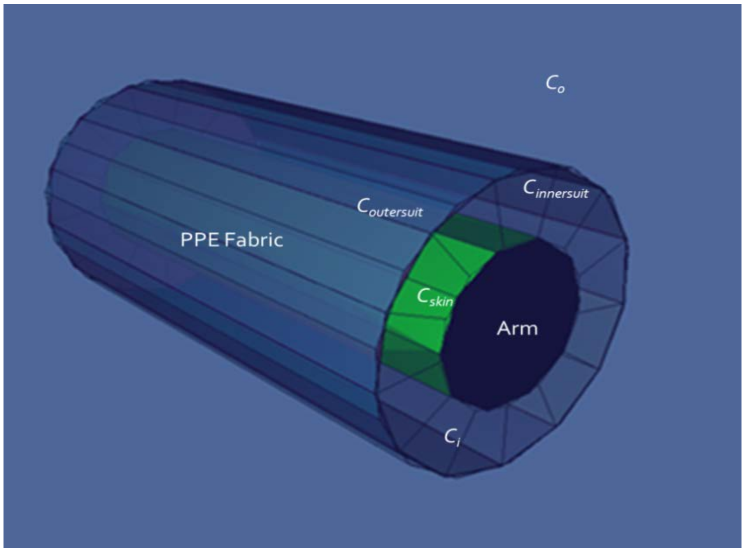

Figure 1: MCNP5 'forearm' model geometry and source terms

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.

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 custom-designed forearm apparatus. The forearm apparatus, composed of aluminum to simulate an air non-permeable fabric, is placed in a large sealed box that is subsequently pumped full of non-radioactive surrogate particulates. One end of the appartus is then opened remotely, allowing the external partuclates to enter the previously vacated forearm volume. 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. Once this experimental data collection is completed, the next step is to develop the corresponding COMSOL model. 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.

The dosimetric model benchmarking was completed with the assistance of the RMCC Analytical Science Group (ASG) as discussed in Reference 7. 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. The experimental set-up and process was then modelled using the MCNP5 software in an attempt to replicate the experimentally-obtained gamma photon transmittance results. As shown in Figure 2, the MCNP5 model is fully consistent with the experimental results over the range of photon energies investigated, given each of their respective uncertainties. As such, the MCNP5 software has been successfully benchmarked for use in the present work.

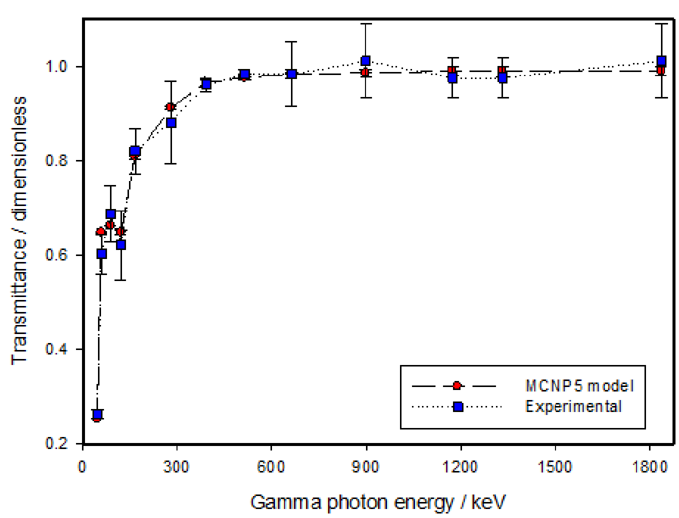

Figure 2: Experimental and MCNP5 transmittance results for a single layer of the second generation CRC fabric [7]

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 with an 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 1, 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 [7], that the PPE materials may be able to offer increased protection capabilities for scenarios involving the emission of low energy photon. It should be noted that this protection does not extend to the photons emitted by the particulates within the confines of the suit, regardless of their energy. Future model development plans to include the five regional concentration values from the particulate transport model, in place of the literature estimates, as source terms in the dosimetric model and include beta radiation considerations.

Table 1: 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

The MCNP5 software has been successfully benchmarked against experimental data, illustrating that the code can be run correctly and is suitable for the dosimetric model. 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. A preliminary MCNP dosimetric model has been successfully developed for radiation hazard scenarios involving radionuclides emitting gamma photons. Future work will seek to incorporate beta radiation into the dosimetric model.

7. References

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