Simulation of Personal Protective Equipment Exposure to Radioactive Particulates

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Summary

Airborne radioactive particulates are a significant hazard facing first responders in nuclear-related incidents. Personal protective equipment (PPE) can be used to reduce wearer exposure to the emitted radiation, but does 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 dose received by the wearer in the event of radiological particulate exposure. A two-fold approach will be employed whereby: (1) a particle transport model will be used to determine the regional radioactive particulate concentrations; and (2) this 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. Future models will consider whole body dose and be invaluable in the development of radiation exposure policies and procedures.

1. Introduction

Throughout history, there have been numerous examples of nuclear-related accidents and incidents. While these events often differ incause and severity, ranging from full scale nuclear reactor meltdowns to the improper disposal of radioisotope sources, it is evident that certain types of radiological hazard scenarios occur more frequently than others. With this in mind, NATO has identified multiple radiological hazard scenarios that pose significant safety risks to the general public and, by extension, the responders to these events [1]. These scenarios differin scale and include the improper disposal of radioisotope sources, dirty bombs, and nuclear weapons strike events; however, in each case, there is a high probability that airborne radioactive particulates will be present.Airborne radioactive particulates are one of the most significant hazards facing first responders in nuclear-related incidents and must be consideredwhen predicting human exposure levels.

The International Commission on Radiological Protection (ICRP) publishes strict guidelines identifying the acceptable exposure limits for both nuclear energy workers (NEWs) and the general population. According to the 1990 Recommendations of the ICRP, NEWs may receive a dose of 100 mSv over a period of five years, with a maximum dose of 50 mSv in any one of those years being deemed acceptable [2]. As one might expect, the ICRP also advises that the general population is to receive a much smaller dose of 1 mSv per year above that contributed by natural background radiation [2].

In order to help meet these recommendations, various types of commercial PPE are marketed with the ability to reduce wearer exposure to radiation hazards by either blocking radioactive particulates or radiation.Unfortunately, most commonly worn PPE suits do not offer complete protection in the event of a radiological hazard scenario; moreover, overtime, radioactive particulates can diffuse through the fabric of the PPE suit or enter the suit through leaks and gaps in improperly sealed closures. As result, there are now radioactive particulates within the protective confines of the PPE suit, which may significantly impact the dose that is imparted to the wearer. In addition, most suit materials do not effectively block all types of radiation.This project seeks to investigate how the presence or absence of a PPE suit (as modelled by a sleeve on an arm) would impact the dose imparted to the wearer in the event of radiological exposure.

2. Project Objective

The objective of this project is to create a realistic dosimetric model of the human arm that can eventually be developed into a tool to assess the dose received by the wearer in the event of radiological particulate exposure. The arm may be covered by an air impermeable or air permeable fabric sleeve, either of which should reduce the particulate deposition onto the skin somewhat. A two-fold modeling approach will be employed whereby: (1) a particle transport model will be used to determine the regional radioactive particulate concentrations; and (2) this 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. 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 have a well-defined range in air and pose less hazard as an external dose while neutrons are not attenuated by current suit materials [3]. Future models will consider whole body dose and may consider all types of radiation in-suit (e.g., alpha, beta, gamma and neutron). These future models will be invaluable in the development of radiation exposure policies and allow for comparison with recommended exposure limits.

3. ‘Forearm’ Model

3.1. Particulate Transport Model

On a fundamental level, particle transport is governed by Fick’s first law. As shown in Equation 1 below, Fick’s first law states that the diffusive flux of some species, J_A, is proportional to the diffusion coefficient, *D*, and concentration gradient of that species, *dc/dx*[4].

$$J_A = -D\frac{dc}{dx} \tag{1}$$

Unfortunately, Fick’s first law is only applicable to steady state diffusion or situations in which the concentration of the species of interest remains constant with time. Because this project is interested in scenarios where the concentration changes with time across an air permeable fabric, it is necessary to move to Fick’s second law. Fick’s second law states that the rate of change of

the concentration, *dc/dt*, is proportional to the diffusion coefficient, *D*, and the rate of change of the concentration gradient, $\nabla^2 c$ [4]. Fick's second law is shown in Equation 2.

$$\frac{dc}{dt} = D\nabla^2 c \tag{2}$$

If Fick's second law is applied to one of the radiological hazard scenarios described earlier, initially there will be a concentration of radioactive particulates in the air outside of the suit and a concentration of particulates that have deposited on surface of the PPE suit. These two regional concentration values will be known as c_o and $c_{outersuit}$, respectively. Overtime, these particulates will diffuse through the fabric of the suit at a rate that is proportional to the diffusion coefficient (*D*) and the rate of change of the concentration gradient ($\nabla^2 c$). In addition, diffusion will occur through the wrist closure, down the forearm. As result, there will be a concentration of radioactive particulates on the inner surface of the PPE 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.

In order to determine each of these regional radioactive particulate concentration values, the COMSOLMultiphysics software will be used. COMSOL is a finite element analysis solver that allows users to couple various physical phenomena with complex geometric designs of realistic environments. Thus, by specifying various parameters such as the particulate diameter, deposition velocity, diffusion coefficient of the PPE fabric, and pressure drop across the fabric, it will be possible to create a COMSOL model that can determine each of the regional concentration values for a static arm covered by an air impermeable or air permeable sleeve, in the presence of wind,as a function of time.

3.2. Dosimetric Model

The dosimetric model developed for this project will use theMCNP-5 software package. MCNP was developed by the Los Alamos National Laboratory (LANL) and is the internationally recognized simulation code for analyzing gamma photon, electron, and neutron transport using the Monte Carlo method. MCNP is a stochastic code that tracks source and secondary particles through user-definedgeometries of realistic environments. It usesa random number generatorand physical probabilities to determine the likelihood that each particle undergoes a nuclear event. Also, the code is capable of tracking secondary particles that are produced as a result of interactions between source particles and the environment. By tracking a large number of particles, MCNP is able to provide the user with the most probable outcome and an associated uncertainty.

Using the MCNP code, it is possible to model and simulate the physical interactions that would occur in a variety of scenarios. From a radiation protection standpoint, the code can be used to calculate a number of different physical quantities such as the particle flux through a surface, the current in a surface, or the dose imparted to a given volume. In this project, MCNP will be employed to determine the dose imparted to a human forearmin the event of radioactive particulate exposurewith and without PPE.

3.3. Determining the Dose Imparted to the Forearm Tissue

In order to calculate the dose that is imparted to human forearm, the five regional concentration values found from the COMSOL particulate transport model (e.g., c_o, $c_{outersuit}$,$c_{innersuit}$,c_i, and c_{skin}) will be incorporated into the MCNP dosimetric model. In this regard, the concentration values will act as source terms in the dosimetric model, whose geometry is shown in Figure 1.

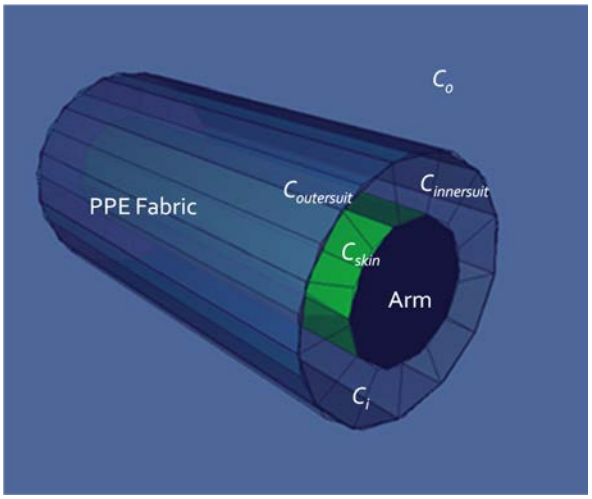

Figure 1: Dosimetric model geometry with accompanying regional concentration values

Using these source terms, it will be possible to use MCNP to determine the dose that is imparted to the forearm tissue in the presence of a PPE fabric. Additional simulations will be run to determine the dose receivedby the tissue in situations where the forearm tissue is unshielded. Thus, it will be possible to determine the effect that PPE suit has on the dose imparted to the human forearm in the event of radioactive particulate exposure.

4. Initial Modelling Results

A preliminary MCNP dosimetric model has been generated using literature estimates for the five regional concentration values. More specifically, these concentration values were obtained from a NATO test scenario simulating the dispersal of a caesium chloride dirty bomb [1]. Using the literature-obtained regional concentration values, two scenarios were simulated. The first involved the release of caesium-137 particulates that emit gamma photons with energy of 661.7 keV. The second scenario involved the hypothetical release of a radioactive particulate that emits gamma photons of 100 keV. For both cases, the dose imparted to the forearm tissue in the presence and absence of a commercially-available PPE fabric, impregnatedwith a thin-tungsten layer [3],was determined. These results are illustrated in Table 1.

This commercially-available PPE suit material was not as effective at attenuating the higher energy gamma photons. Consequently, the dose received for the 661.67 keV photons by the forearm was almost equivalent regardless of the presence of the PPE fabric. Conversely, for the lower energy gamma photons (100 keV), the dose was reduced by 30%.Therefore, the commercially-available PPE suit material was able to attenuate some of the lower energy incident gamma photons.

Table1: Summary of initial modeling results

Photon Energy / keV	Shielding	Dose Rate / mSv hr^{-1}	Reduction of Intensity / %
661.67	No Shielding	0.239 ± 0.003	< 1
	Commercial PPE	0.237 ± 0.003	
100	No Shielding	0.0289 ± 0.0003	30
	Commercial PPE	0.0203 ± 0.0003	

5. Future Benchmarking Experiments

As a large portion of this project is based on computer modelling and simulation, it will be necessary to conduct benchmarking experiments. Experiments will be required for both the particulate transport model and dosimetric model. The RMCC CBRN Protection Group will assist in the validation of the particulate transport model, while the RMCC Analytical Science Group will assist in the validation of the dosimetric model. Planning for the above benchmarking experimentation is underwaycurrently.

6. Summary

A preliminary MCNP dosimetric model has been successfully developed for gamma photons. Additional effort is required to develop the COMSOL particulate model. It will also be necessary to conduct a thorough review of the literature in order to identify all of the pertinent variables that need to be included in the particulate transport model. Once accomplished, it will then be possible to begin developing the particulate transport model such that the five regional concentration values can be determined and incorporated into the dosimetric model. Also, further development is required for radioactive particulate modellinginvolving beta emitters(e.g., Sr-90). Also, model validation via comparison to the benchmarking experiments will be completed.

7. Acknowledgements

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