RADIATION EXPOSURE OF WORKERS AND VOLUNTEERS IN SHELTERS AND COMMUNITY RECEPTION CENTERS IN THE AFTERMATH OF A NUCLEAR DETONATION

Jeri L. Anderson,[1] Gregory Failla,[2] Lauren R. Finklea,[3] Paul Charp,[4] and Armin J. Ansari[3]

Abstract—**After a nuclear detonation, workers and volunteers providing first aid, decontamination, and population monitoring in public shelters and community reception centers will potentially be exposed to radiation from people they are assisting who may be contaminated with radioactive fallout. A state-of-the-art computer-aided design program and radiation transport modeling software were used to estimate external radiation dose to workers in three different exposure scenarios: performing radiation surveys/decontamination, first aid, and triage duties. Calculated dose rates were highest for workers performing radiation surveys due to the relative proximity to the contaminated individual. Estimated cumulative doses were nontrivial but below the occupational dose limit established for normal operations by the Occupational Safety and Health Administration.**
Health Phys. 00(00):000–000; 2019

Key words: emergency planning; exposure, occupational; fallout; modeling, dose assessment

INTRODUCTION

To PREPARE for a response to a nuclear detonation, several national-level exercises have been held in cooperation with many US government agencies, state and local governments, and nongovernmental organizations such as the Red Cross and the Salvation Army. In the event of such an incident, hundreds of thousands of people may require immediate evacuation from the affected area while tens of thousands of people will seek shelter from extremely high radiation levels in the damage zones/dangerous fallout zones. People sheltered in place in the damage zones/dangerous fallout zones will need to be evacuated as soon as the fallout plume has passed over and dose rates have decayed to a less hazardous level (~20% to 5% of the radiation levels postdetonation at 24 to 72 h, respectively). Evacuees may be directed to community reception centers (CRCs) and then to either a public shelter, a hospital for medical care, or to their homes if they are located outside the zones that have been identified for evacuation and/or relocation by the responding authorities. During the course of evacuation, either immediately after detonation or after sheltering in place for a brief period, the evacuees will likely be exposed to elevated levels of external ionizing radiation from fallout deposited on the ground (i.e., ground shine) and other surfaces, and can themselves become contaminated with radioactive fallout. The contaminated evacuees may pose a potential health risk to other members of the public outside the affected area and to shelter and CRC workers. Safety officers and responsible emergency response agencies need to address the safety and health of the workers and volunteers providing first aid, decontamination, and population monitoring in public shelters and CRCs.

The purpose of this project was to model the potential radiation exposure to workers and volunteers in these facilities using state-of-the-art computer-aided design (CAD) and radiation transport modeling software. Better characterization of the radiation environment in public shelters and CRCs and a more precise estimate of dose to workers and volunteers helps to inform decision making and develop recommendations to ensure their safety and health.

METHODS

Three different three-dimensional exposure scenario models were created using the CAD software ANSYS SpaceClaim (version R18.0; SpaceClaim Corporation, Concord, Massachusetts, US). The three scenarios considered were:

[1]Division of Surveillance, Hazard Evaluations and Field Studies (DSHEFS), National Institute for Occupational Safety and Health (NIOSH); [2]Varex Imaging, Inc.; [3]Emergency Management, Radiation and Chemical Branch, Division of Environmental Health Science and Practice, National Center for Environmental Health, Centers for Disease Control and Prevention; [4]Division of Community Health Investigations, Centers for Disease Control and Prevention, Agency for Toxic Substances and Disease Registry.

The authors declare no conflicts of interest.

For correspondence contact Jeri L. Anderson, NIOSH/DSHEFS, 1090 Tusculum Avenue, MS R-14, Cincinnati, OH 45226, or email at **JLAnderson@cdc.gov**.

(*Manuscript accepted* 29 *August* 2018)
0017-9078/19/0

DOI: 10.1097/HP.0000000000000987

- A worker performing a radiological contamination survey in close proximity to a contaminated individual (survey model);
- Workers providing first aid in close proximity to a contaminated individual in a shelter or CRC (first-aid model); and
- A worker performing triage duties on potentially contaminated individuals at the entrance to a CRC or shelter (triage model).

SpaceClaim was used to design a source phantom representing a contaminated individual with a height and surface area equivalent to the reference adult male described by the International Commission on Radiological Protection (ICRP 2002). The source phantom included a 1-mm-thick shell over the entire surface of the phantom (annular surface), which contains the simulated fallout contamination. Phantoms designed to represent the workers were identical with the exception of lacking the 1-mm annular surface. In order to estimate the effect of source phantom size on the dose rate, three additional source phantoms were designed to represent a 5-y-old male/female child, a 10-y-old male/female child, and a 15-y-old male/adult female. These additional source phantoms have height and surface area similar to the ICRP reference children and adults and were designed with the 1-mm annular surface to hold contamination.

The three CAD scenario models created in SpaceClaim were imported into Attila (version 9.0.2; Varex Imaging Corporation, Salt Lake City, Utah, US) for calculation of worker doses by deterministically solving the linear Boltzmann transport equation:

$$\hat{\Omega}\cdot\vec{\nabla}\Phi + \sigma_t\Phi = Q^{scat} + Q^{ext}, \qquad (1)$$

where Φ is the energy- and angular-dependent particle fluence, and $\hat{\Omega}\cdot\vec{\nabla}\Phi$ is the streaming operator representing the net number of particles flowing in a volume element dV in a direction $\hat{\Omega}$ about $d\hat{\Omega}$ with energy E about dE. The sources on the right side of eqn (1) include both external sources and scattering sources. Attila discretizes the equation in space, angle, and energy, then iterates to convergence.

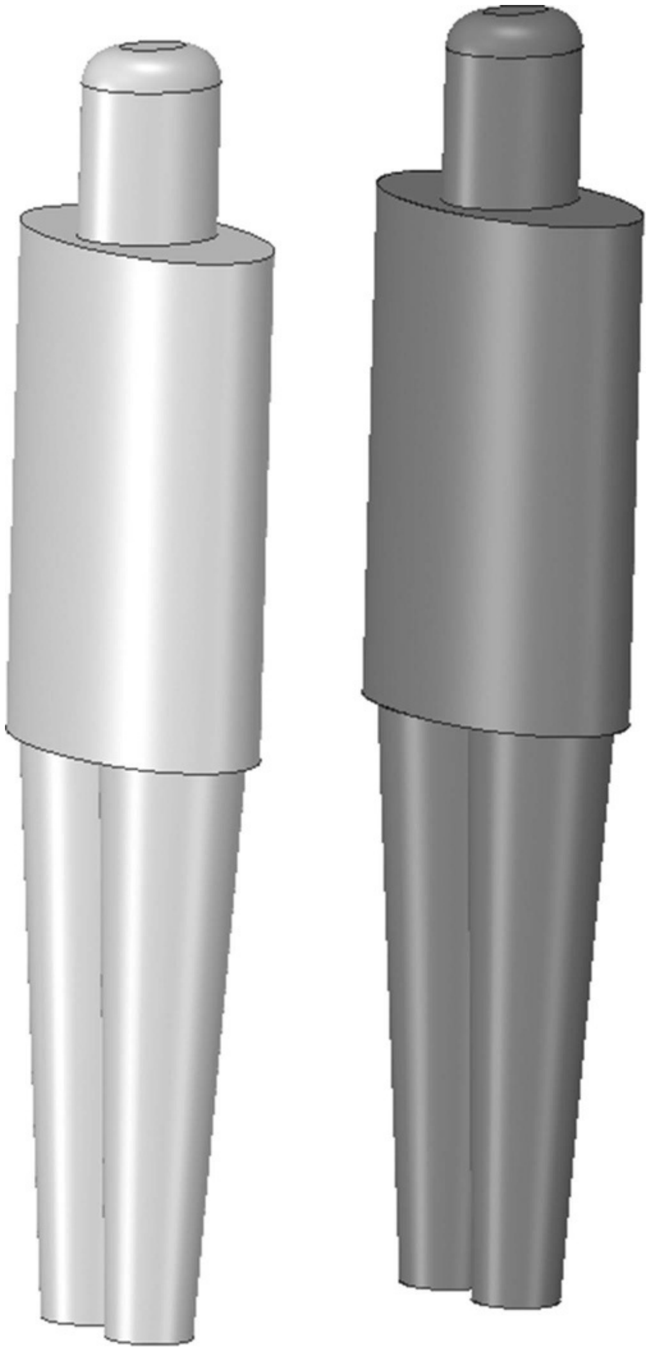
The calculation involves first generating a computational mesh made up of body-fitted tetrahedral elements (space discretization). Because Attila calculates a solution everywhere, each CAD model was enclosed in a defined air region by creating a box around the internal components of the model. The size of the tetrahedral elements that make up the mesh are determined by the tetrahedral element edge length, which was set at a maximum of 0.2 m for most of the mesh regions and at 0.05 m for areas of dosimetric interest such as the phantom regions. Automatic curvature refinement was used by setting the value of distance (d) from the element edge to the surface over the edge length (h) to 0.02 to capture surface curvature. The refinement was done anisotropically so elements were only refined in the direction of curvature. The curvature refinement minimum edge length was set at 0.05 m.

Attila assigns a material cross section to every element in the computational mesh, and all elements in the same CAD region are assigned the same cross sections. These cross sections are dependent on material type, particle type, and particle energy. The density, elemental composition, and element weight fractions of the materials of interest (Cristy and Eckerman 1987; Williams et al. 2006) were used to assign appropriate cross sections. Each of the CAD regions in the three models were assigned one of these materials. The fallout was simulated using ordinary concrete for the elemental composition with the density of 1.6 g cm^{-3} to represent the consistency of fine, dry sand. The effect of varying the density and elemental composition of the source matrix on the estimated dose rate was evaluated by comparing dose rates calculated using air and soil as the matrix.

Parameters were also specified for angle and energy discretization. Attila uses the discrete-ordinates method for angular discretization. Angular quadrature order (S_N order) was set to 16, giving 288 (or $N^2 + 2N$) angles per unit sphere (default triangular Chebychev Legendre quadrature set). The scattering degree, or spherical harmonics expansion order (P_n order), represents anisotropy in the scattering source and was set to 2. For energy discretization, the fine energy group structures in the cross section file were collapsed into eight coarse groups for energies less than the maximum source energy. Groups higher than the maximum source energy were not included in the calculation as there was no possibility of scatter into those groups.

To define a radiation source for these calculations, primary exposure of workers was assumed to be due to gamma radiation from fallout-contaminated members of the public. The detonation was assumed to be from a 10-kT improvised nuclear device at ground level in the downtown area of a major city. A fixed volumetric source was placed in the 1-mm annular surface of the source phantom with a source strength of 1 particle s^{-1}. A reasonable estimate of average gamma ray energy at 1 h after the explosion is about 0.7 MeV (Glasstone and Dolan 1977), so the source spectrum was defined as monoenergetic gamma rays with an energy of 0.662 MeV, representative of the ^{137m}Ba gamma spectrum from the decay of ^{137}Cs.

Attila was then run to calculate the fluence rate in each model. Attila solves for the angular- and energy-dependent gamma flux in every computational element of the mesh. The dose rate (Sv h^{-1}) per unit source particle in each mesh region was then estimated by multiplying the ICRP 74 fluence-to-ambient dose equivalent conversion coefficients (ICRP 1996) by the average fluence rate in each mesh

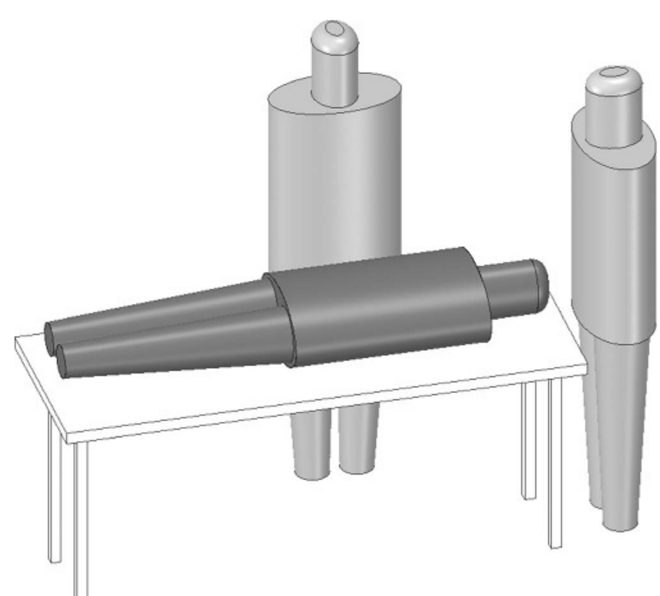


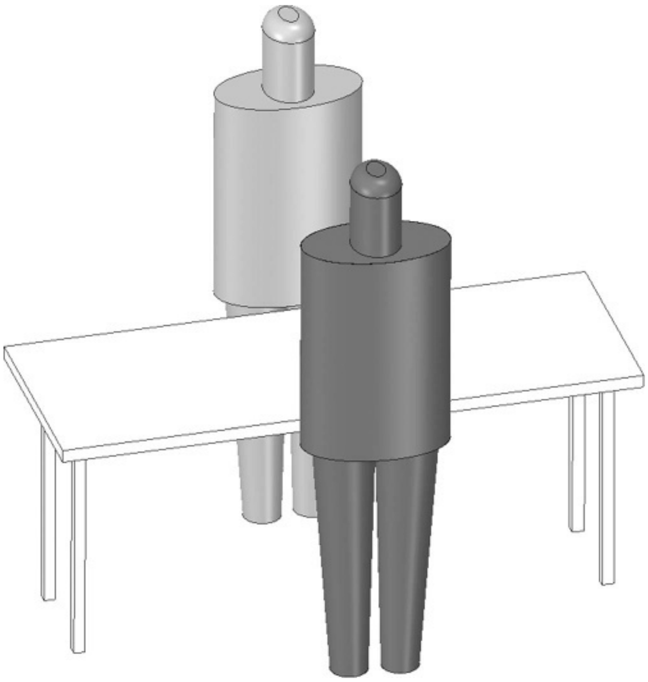
element of that region. Although these conversion coefficients were meant to be applied to free-field fluence, the ambient dose equivalent is an operational quantity that overestimates effective dose by 15% or more. To evaluate the effect of using the conversion coefficients with tissue fluence, absorbed dose rate was also calculated for the worker in the survey model by applying the fluence calculated in tissue to conversion coefficients calculated using energy fluence and mass-energy absorption coefficients. The dose rate per unit source particle was then scaled according to the estimated activity of the fallout contamination on the patient.

It has been calculated that the level of gamma radiation in fallout at 1 h after an explosion can be approximated to be about 1.96×10^{19} Bq kT^{-1} fission yield (Glasstone and Dolan 1977). This early fallout was assumed to deposit uniformly over 2.6 km^2 surrounding the detonation. This activity was then reduced according to the decay equation for fallout radiation (Glasstone and Dolan 1977):

$$A_t = A_0 t^{-1.2}, \quad (2)$$

where A_0 is the activity at $t = 1$ h and A_t is the activity after time t. It was assumed that most of the population coming to shelters and CRCs will have sheltered in place for the first 48 h after the detonation. The personal contamination was assumed to arise from the individual walking through fallout-contaminated areas causing resuspension of materials and then some fraction of that suspended material depositing on the surface of the individual. A conservative resuspension factor of 7×10^{-4} m^{-1} was assumed (Sehmel 1980). The maximum total activity (Bq) depositing on the surface of the individual, regardless of time spent outside, was calculated by multiplying the activity of the fallout contaminating the ground surfaces (Bq m^{-2}) by the resuspension factor (m^{-1}) and by the total volume (m^3) of the annular surface of the individual. This contamination activity, assumed to be uniformly distributed over the surface of the phantom, was then multiplied by the dose rate per unit source particle calculated in Attila. Total dose for each worker in each of the three models was estimated after 8 h





(1 working day) of exposure and 40 h (1 working week) of exposure.

RESULTS

The three-dimensional CAD models are graphically illustrated in Figs. 1–3, and the dimensions of the models and annular source volumes are shown in Table 1. In the survey model (Fig. 1), the worker is standing 33 cm from the contaminated individual. In the first-aid model (Fig. 2), both workers are standing 5 cm from the edge of the table. The front surface of the worker positioned at the patient's head is about 11 cm from the nearest surface of the patient, and the worker positioned at midtorso is about 17 cm from the patient. In the triage model (Fig. 3), the front surface of the worker is 3 cm from the table and 76 cm from the nearest surface of the contaminated individual. Table 2 shows the materials used for each of the CAD components and the corresponding densities and elemental compositions.

The radioactivity of the fallout in a 2.6-km^2 area after detonation of a 10-kT fission device was estimated to be 8.13×10^{13} Bq m^{-2} at 1 h after the explosion. So, at 48 h after the explosion, the radioactivity of the fallout had decayed to 7.81×10^{11} Bq m^{-2}. Conservative estimates of individual fallout contamination for source phantoms were 81 MBq for the 5-y-old male/female, 104 MBq for the 10-y-old male/female, 130 MBq for the 15-y-old male/adult female, and 158 MBq for the adult male. Table 3 shows the Attila-calculated dose rates to the worker per source particle (gamma per disintegration of $^{137}Cs/^{137m}Ba$) in each of the CAD models as well as the estimated dose rate and total dose at 8 h and 40 h for workers exposed to a fallout-contaminated individual. Workers were conservatively assumed to occupy the position at which the dose rates were calculated for the entire dose accumulation period.

Choice of material for the fallout matrix did not result in significant variation in dose rate. Use of air instead of concrete as the matrix resulted in a slight increase in dose rate (~2.6%). Use of soil as the matrix did not significantly change the dose rate. Also, use of fluence to ambient dose equivalent conversion coefficients overestimated absorbed dose by about 16%.

DISCUSSION

The modeling of external exposure from fallout is not straightforward as the physical, chemical, and radiological characteristics of the fallout material depend on the type, height, and yield of the nuclear detonation (Glasstone and Dolan 1977). In this scenario, the detonation was assumed to be a ground-level blast, which results in a significant amount of building materials and other debris being drawn

Table 1. Dimensions of CAD model components.

Component	Length (cm)	Width (cm)	Height (cm)	Annular source volume (m^3)
Adult male source phantom/worker			176	0.29
Adult female/15-y-old source phantom			161	0.24
10-y-old source phantom			135	0.19
5-y-old source phantom			112	0.15
Table—first-aid and triage models	187	69	81	
Floor—survey model	200	200	5	
Floor—first-aid model	350	350	5	
Floor—triage model	350	350	5	
Air region—survey model	200	200	200	
Air region—first-aid model	350	350	200	
Air region—triage model	350	350	200	

Table 2. Elemental composition (weight fraction) of materials used in radiation transport calculations.

Material	Human body	Soil	Concrete[a]	Wood	Air
Mesh regions	Worker, source phantoms	Fallout	Floor	Table	Void, fallout
Density (g cm^{-3})	1.04	1.6	2.3	0.673	0.0012
H	0.10052	0.021	0.0056	0.057889	
C	0.22922	0.016		0.482667	
N	0.02442				0.755
O	0.61289	0.577	0.4983	0.459444	0.232
Na	0.0014		0.0171		
Mg	0.00027		0.0024		
Al		0.05	0.0456		
Si		0.271	0.3158		
P	0.00835				
S	0.00216		0.0012		
Cl	0.00137				
Ar					0.013
K	0.00202	0.013	0.0192		
Ca	0.01728	0.041	0.0826		
Fe	0.0006	0.011	0.0122		

[a]When used as the fallout matrix in the 1-mm annular surface region, concrete was assigned a density of fine sand (1.6 g cm^{-3}).

into the fireball. The source of the radiation is primarily from fission product radionuclides and, to a lesser extent, radionuclides created by neutron activation. The activity of the fallout depends on the nature of the fissionable material and the energy of the neutrons causing the fission reaction. For example, the relative activities of radionuclides produced by the fission of ^{238}U as the result of high-energy neutrons from thermonuclear fusion reactions are somewhat different than the relative activities of radionuclides produced by the fission of ^{235}U from ordinary fission neutrons. The fission products are a mixture of more than 200 isotopes of about 36 different elements with atomic numbers between 28 and 65, which decay to stable elements by emitting beta radiation usually accompanied by gamma rays (Klement 1965). In addition to the fission products, other radionuclides are produced as a result of neutron interactions with stable elements in building materials, soil, water, and air, though only a few of these radionuclides are present after the first 24–48 h after the detonation. Glasstone and Dolan (1977) report that a reasonable estimate of average gamma ray energy (E) for fallout radiation is about 0.7 MeV, so the use of ^{137m}Ba gamma spectrum ($E = 0.662$ MeV) from the decay of ^{137}Cs is a reasonable approximation.

The estimated dose rate for the worker located at midtorso in the first-aid model (0.19 mSv h^{-1} [GBq m^{-2}]$^{-1}$) was similar to that obtained by Smith et al. (2005) and Burns et al. (2009) for a surgeon operating on a patient (at midtorso) with uniform surface contamination from ^{137}Cs after a radiological dispersal device (RDD) incident. The Smith et al. and Burns et al. studies estimated a dose rate

Table 3. Attila-calculated dose rates per unit source particle, dose rate at assumed contamination level, and estimated daily and weekly dose to workers calculated for workers in CRCs and shelters. Workers were conservatively assumed to occupy the position at which the dose rates were calculated for the entire dose accumulation period.

Scenario	Dose rate per source particle (pSv h^{-1})	Dose rate at assumed contamination level (mSv h^{-1})	Total dose at 8 h (mSv)	Total dose[a] at 40 h (mSv)
Survey model				
Worker-adult male source	0.11	0.017	0.13	0.66
Worker-female/15-y-old source	0.12	0.016	0.13	0.63
Worker-10-y-old source	0.13	0.013	0.11	0.53
Worker-5-y-old source	0.13	0.010	0.082	0.41
First-aid model				
Worker at head	0.061	0.0096	0.077	0.39
Worker at midtorso	0.10	0.015	0.12	0.61
Triage model				
Worker	0.047	0.0075	0.056	0.30

[a]Differences in total dose obtained by multiplication are attributed to rounding errors.

per unit surface contamination of 0.27 mSv h^{-1} (GBq m^{-2})$^{-1}$ using the MicroShield program (Grove Software, Lynchburg, Virginia, US) and 0.19 mSv h^{-1} (GBq m^{-2})$^{-1}$ using Monte Carlo N-Particle (MCNP) methods, respectively. The difference in dose rate with the Smith et al. study is likely due in some part to the dissimilarity in source phantom geometry. The level of contamination on the victims/patients from resuspended fallout 2 d after detonation estimated in this study (0.082–0.10 GBq m^{-2}) was less than that estimated by Smith et al. and Burns et al. (0.37–37 GBq m^{-2}) for contamination immediately following detonation of an RDD containing ^{137}Cs.

No shielding from clothing worn by the worker or from hospital bed sheets was accounted for in the calculations for this study, as any contamination was assumed to be on the surface of the clothing or on exposed skin and hair. Realistically, contamination would vary over the surface of the individual; however, for these calculations, uniform distribution of contamination was assumed. Also, workers were assumed to be using standard precautions for infection control, which would reduce potential for external and internal contamination of the workers. Skin dose was also not accounted for but was assumed to be minimal for workers in these scenarios. Thus, only external ionizing radiation from the source phantoms were considered to contribute to worker dose.

The US Occupational Safety and Health Administration (OSHA) in its ionizing radiation standard 29 CFR 1910.1096 (OSHA 2018) limits worker dose to 12.5 mSv per quarter. With a conservatively estimated dose rate of 0.017 mSv h^{-1}, a worker would have to be continuously surveying contaminated individuals for more than 10 h d^{-1} and 6 d wk^{-1} for an entire quarter to exceed the OSHA dose limit. Depending on the number of workers and volunteers available to staff public shelters and CRCs during an extended emergency, it is possible that work shifts could consist of 10- to 12-h days, 6–7 d wk^{-1}. However, the dose rates estimated were for maximum levels of contamination, which would be improbable as most individuals entering shelters and CRCs 48 h after the detonation would likely have been sheltering in place in other locations and would have performed self-decontamination if needed. Shelter and CRC workers can further minimize their exposure by having individuals with visible contamination remove outer layers of clothing before entering the shelter or CRC and before contamination surveys are performed.

CONCLUSION

Radiation dose was estimated for workers in three different scenarios thought to have the highest potential for exposure when working in shelters and CRCs during a response to a nuclear detonation in a large metropolitan area. Workers were assumed to come in closest contact with contaminated members of the public when surveying individuals for contamination and when performing first aid and triage activities. The highest exposure occurs during contamination surveying as this places the worker in closest proximity to a radiation source. All dose rates were nontrivial, but estimated cumulative doses to workers and volunteers in CRCs following a nuclear detonation were well below the OSHA quarterly occupational dose limit for normal operations.

Acknowledgments—The authors thank Terrence Kraus and Nolan Hertel for their thoughtful review and suggestions.

DISCLAIMER—The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the Centers for Disease Control and Prevention, Agency for Toxic Substances and Disease Registry.

REFERENCES

Burns K, Hertel N, Ansari A. Monte Carlo simulations to determine doses to healthcare providers after a radiological dispersal device event. Nucl Technol 168:820–823; 2009.

Cristy M, Eckerman KF. Specific absorbed fractions of energy at various ages from internal photon sources. I. Methods. Oak Ridge, TN: Oak Ridge National Laboratory; ORNL/TM-8381/V1; ORNL/TM-8381/V1; 1987.

Glasstone S, Dolan PJ. The effects of nuclear weapons. Washington, DC: US Department of Defense and the Energy Research and Development Administration; 1977.

International Commission on Radiological Protection. Conversion coefficients for use in radiological protection against external radiation. Oxford: Pergamon; Publication 74; 1996.

International Commission on Radiological Protection. Basic anatomical and physiological data for use in radiological protection: reference values. Oxford: Pergamon; Publication 89; 2002.

Klement AW Jr. Radioactive fallout phenomena and mechanisms. Health Phys 11:1265–74; 1965.

Sehmel GA. Particle resuspension: a review. Environ International 4:107–127; 1980.

Smith JM, Ansari A, Harper FT. Hospital management of mass radiological casualties: reassessing exposures from contaminated victims of an exploded radiological dispersal device. Health Phys 89:513–20; 2005.

US Occupational Safety and Health Administration. Ionizing radiation. Washington, DC: US Government Printing Office; 29 CFR Part 1910.1096; 2018.

Williams RG, Gesh CJ, Pagh RT. Compendium of material composition data for radiation transport modeling. Richland, WA: Pacific Northwest National Laboratory; PNNL-15870; PNNL-15870; 2006.

■■