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APPLICATION OF THE MASH 1.0 CODE SYSTEM TO RADIOLOGICAL WARFARE RADIATION THREATS*

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ABSTRACT

Nuclear hardening capabilities of U. S. and foreign ground force systems is a primary concern of the Department of Defense (DoD) and U. S. Army. The Monte Carlo Adjoint Shielding Code System - MASH v1.0 was developed at Oak Ridge National Laboratory (ORNL) to analyze these capabilities, i.e. the shielding effectiveness, for prompt radiation from a nuclear weapon detonation. Rapidly changing world events and the proliferation of nuclear weapons related technology have increased the kinds of nuclear threats to include intentionally dispersed radiation sources and fallout from tactical nuclear weapons used in the modern AirLand battlefield scenario. Consequently, a DoD area of increasing interest focuses on determining the shielding effectiveness of foreign and U. S. armored vehicles to radiological warfare and fallout radiation threats.

To demonstrate the applicability of MASH for analyzing dispersed radiation source problems, calculations have been completed for two distributed sources; a dispersed radiation environment simulated by a uniformly distributed ^{60}Co source, and a ^{235}U fission weapon fallout source. Fluence and dose assessments were performed for the free-field, the inside of a steel-walled two-meter box, in a phantom standing in the free-field, and in a phantom standing in the two-meter box. The results indicate substantial radiation protection factors for the ^{60}Co dispersed radiation source and the fallout source compared to the prompt radiation protection factors. The dose protection factors ranged from 40 to 95 for the two-meter box and from 55 to 123 for the mid-gut position of the phantom standing in the box. The results further indicate that a ^{60}Co source might be a good first order approximation for a tactical fission weapon fallout protection factor analysis.

I. INTRODUCTION

Nuclear hardening capabilities of U. S. and foreign ground force systems is a primary concern of the Department of Defense (DoD) and U. S. Army. The Monte Carlo Adjoint Shielding Code System - MASH v1.0[1] was developed at Oak Ridge National Laboratory (ORNL) to analyze these capabilities, i.e. the shielding effectiveness, for prompt radiation from a nuclear weapon detonation. MASH calculates the neutron and gamma-ray environments and radiation protection factors for armored vehicles, structures, and other shielded assemblies of interest to DoD. The shielding effectiveness can be characterized for both personnel and electronic equipment as a function of weapon parameters (yield, height-of-burst, source-to-target range, etc.) and the orientation and configuration of the target for both tactical and strategic weapon laydowns.

For prompt radiation environments, MASH has been extensively benchmarked through comprehensive comparisons with measured data obtained at the Army Pulsed Radiation Facility (APRF) at Aberdeen Proving Ground, Maryland. Several experimental configurations have been studied including, the Soviet Armored Infantry Fighting Vehicle (BMP-'), the U.S. Abrams Tank (Version

XM-1 and M1A1), and two steel-shielded assemblies: the Radiological Test Configuration (RTK)[2] and the Two-Meter Box Test-Bed Assembly.[3-5] Additionally, MASH has been used to calculate crew protection factors for the U. S. M60A1[6] and crew and electronic component protection factors for the U. S. M1A1 and M1A2 Abrams Main Battle Tanks in an initial radiation environment. MASH v1.0 has been adopted by the NATO Panel VII Ad Hoc Group of Shielding Experts as the reference code for <u>all</u> (NATO and non-NATO) armored vehicle prompt radiation nuclear vulnerability calculations, and is the reference code of choice as stated in the recent update to the U. S. Army's Qualified Research Requirements (QRR).

Rapidly changing world events and shifts in the balance of nuclear power have increased the nuclear threats to include intentionally dispersed radiation sources and fallout from tactical nuclear weapons used in the modern AirLand battlefield scenario. With these new threat scenarios, strategic or tactically vital territories may be polluted with gamma-ray emitting isotopes of sufficient magnitude and intensity to preclude traversal by unprotected casual or military personnel. Consequently, a DoD area of increasing interest focuses on determining the shielding effectiveness of foreign and U. S. armored vehicles to these radiological warfare and fallout radiation threats. This paper provides an overview of the application of MASH to radiological warfare radiation threats.[7]

II. COMPUTATIONAL METHODOLOGY

A typical MASH problem involves analyzing a target (armored vehicle, building, etc.) in a prompt radiation field. MASH employs a forward discrete ordinates calculation to determine the neutron and gamma-ray fluence on a coupling surface surrounding the armored vehicle or shielded structure and an adjoint Monte Carlo calculation to determine the dose importance of the surface fluence. MASH then utilizes a processing code to fold the fluence together with the dose importance to yield the desired detector response(s) (dose, radiation damage, latchup, etc.). The data flow diagram of the MASH v1.0 code system applied to a typical prompt radiation problem is given in Figure 1.

In the prompt radiation problem, the neutron and gamma-ray sources originate at a single point, typically located at some height-of-burst above the terrain. To avoid complications (e.g. ray effects) inherent in calculating point sources in a low scattering media such as air using the method of discrete ordinates, the GRTUNCL[8] code is utilized to calculate the first collision source and uncollided fluence for all points in the spatial mesh (Refer to Figure 1). The first collision source is then utilized in the discrete ordinates code DORT[8] as a spatially distributed source and yields a fluence solution void of ray effects for all mesh space. For the radiological warfare or fallout radiation problem, the radiation source is already distributed on the surface of the terrain and/or target geometry and in some instances acts as a volumetric source when the thickness of the fallout or dispersal debris is sufficiently large. Consequently, the GRTUNCL code is not needed for the calculation of the radiation environment. With the minor modification of omitting the GRTUNCL calculation from the data flow diagram in Figure 1, a radiation dispersal or nuclear fallout problem can be solved with MASH following the rest of the data flow diagram. This illustrates one of the major benefits of MASH for performing nuclear vulnerability analyses. In particular, the same adjoint Monte Carlo calculation (right-hand side of Figure 1) of the neutron and gamma-ray leakage from the armored vehicle or shielded structure can be utilized (folded) with a number of different sources including prompt, delayed, fallout, dispersal, etc.. This flexibility in MASH allows the analyst a complete capability in characterizing the radiation hardness of an armored vehicle in operation on the modern AirLand nuclear battlefield.

A. Parameter Optimization

Utilizing MASH for analysis of a dispersed radiation source requires a different problem setup in terms of angular quadrature, mesh spacing, and input parameters than that used for the analysis of a prompt radiation source. The dispersed radiation source conceptually requires a more radially peaked angular quadrature set to account for contributions to the dose due to source particles originating as a function of range from the target. The contributing source range and effects of source depth also should be quantified to determine optimum source input parameters to use in

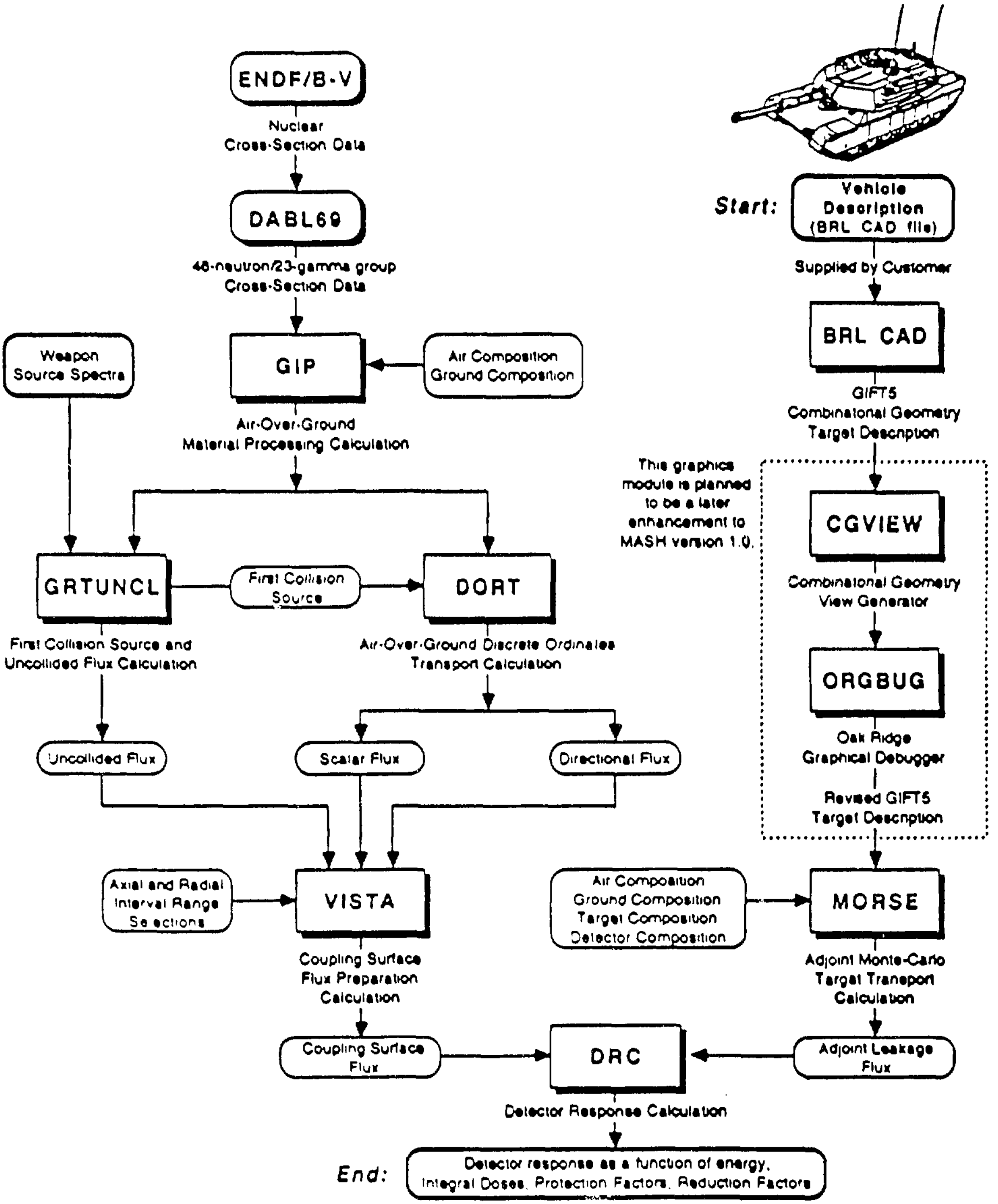

Figure 1. Data Flow Diagram of the MASH 1.0 Code System Applied to a Typical Prompt Radiation Analysis.

a typical analysis. To optimize the parameters in the calculation of the dispersed radiation environment, a ^{60}Co source was uniformly distributed in a thin (0.1 cm) layer of ground. Modeling sensitivities with respect to angular quadrature, mesh size, and source description (thickness and distance from target) were analyzed to optimize the calculations. The ^{60}Co source was chosen because; (1) an analytic solution could be determined for the free-field fluence, and (2) because a forward MORSE[9] calculation could also be used to verify the discrete ordinates model used in the MASH analysis.

The baseline air-over-ground model for the dispersed radiation parameter optimization analysis utilized 200 radial intervals and 100 axial intervals in a flat topographical r-z model. This mesh modeled a 2000 meter by 2000 meter air environment. Approximately 55 cm of ground was included in the air-over-ground calculations to account for ground scattering. The axial mesh varied as a function of height above (and below) the ground with a maximum mesh size of 30 meters. The radial mesh size was constant at 5 meters. The source was initially set with a thickness of 0.1 cm on the air/ground interface and uniformly distributed in the radial mesh. The air-over-ground model utilized a P_5 Legendre expansion of the cross sections, the reference DNA DABL69 46neutron 23 gamma ray group cross-section library,[10] and air and ground typical of that found at the APRF.

Parameter optimization analyses results indicate that for detector heights greater than 1.0 meter above the ground, the 240-direction quadrature set used in prompt radiation analysis is adequate. If the detector height is less than 1.0 meter above the ground, a radially biased direction set is required to properly account for all of the source contributing to the detector response. The results also indicate radial mesh spacing (up to 5 meters) has a negligible effect on the fluence for detector heights typical of armored vehicles (e.g. detector heights ranging from 1 to 2 meters above the ground). The sensitivity to radial mesh was not analyzed for radial mesh cells greater than 5 meters because this mesh spacing was determined to be optimum for armored vehicle analyses in the 2000 meter by 2000 meter air-over-ground environment used in this analysis.

The sensitivity to source thickness was quantified for the idealized uniformly distributed ^{60}Co source distribution by varying the source thickness. The results indicate the effects of source depth thickness were negligible for sources ranging from 0.01 cm to 0.1 cm thick. The two source thickness extremes indicated differences for the free-field fluence less than 5% in the energy groups above 1.0 MeV. In a real contaminated ground area, the distribution will probably be non-uniform in thickness and in radial distribution from the origin of the detonation. To gage the size of the source area to be included in a model, the free-field uncollided fluence from the uniformly distributed ^{60}Co source was chosen as an appropriate guideline since it yields the absolute range of a contributing source particle. The effects of source range indicate 97% of the free-field fluence can be obtained by modeling the source in a radius of approximately 200 meters for a detector 1.25 meters above the ground. Further optimization of the contributing source range and thickness should be performed for different sources and different detector heights.

III. APPLICATION TO THE TWO-METER BOX AND PHANTOM

To demonstrate the applicability of MASH in analyzing dispersed radiation source problems, calculations have been completed for two radiation sources distributed on flat ground. First, the ^{60}Co source used above in the parameter optimization study, uniformly distributed in a 0.1 cm layer of ground, was used to simulate a radiation dispersion weapon. Second, an ORIGEN[11] generated fallout source from a nuclear weapon detonation was used to generate the secondary photon distribution as a function of time after burst. Time steps of 4 hours, 24 hours, and 72 hours were analyzed using MASH with the same modeling parameters optimized in the ^{60}Co analyses. For both sources, fluence and dose assessments were performed for the free-field, the two-meter box, the phantom standing in the free-field, and the phantom standing in the two-meter box. The in-box results were obtained for a detector located in the center of the box. The in-phantom results were obtained for the mid-gut (MG) position on the phantom. Each MORSE case initiated 1,000,000 source particles (1000 particles/batch and 1000 batches). Analyzing 1,000,000 source particles yielded integral data statistics within 5% and spectral data statistics within 15% for the geometries considered.

A. The Two-Meter Box Test Bed and RT-200 Anthropomorphic Phantom

The "NATO standard test bed" is a large cubical steel-walled box having interior dimensions of 200 cm x 200 cm x 200 cm and wall thickness (top and sides) of 5.08 cm. The bottom plate is 10.16 cm thick. The top and side wall thicknesses can be increased to 10.16 cm by the addition of 5.08 cm thick steel plates. Hatches are located in the center of the top and back faces of the box and the hatch diameters in the interior box and outside plates are staggered to mitigate radiation streaming paths into the box. The hatches are included for loading and unloading experimental equipment (e.g. detectors, phantoms, etc.) and for simulating open-hatch vehicle experiments. The interior air space volume with dimensions of 200 cm x 200 cm x 200 cm gives the test bed the common name - "the two-meter box."

The phantom used in prompt radiation measurements at the APRF is the RT-200 anthropomorphic phantom supplied by the Defence Research Establishment Ottawa, Canada (DREO). The RT-200 phantom is a complex form which does not lend itself easily to modeling using standard combinatorial geometry input currently available in MASH. Consequently, a modified combinatorial geometry phantom model was used in the MASH analysis. The combinatorial geometry model represents a simplified form of the RT-200 phantom and does not have all the detailed contours which characterize the RT-200. The simplified phantom model is 174.4 cm tall and weighs approximately 70.0 kg. The chest contains a set of lungs and has a depth and width of 20.0 cm and 34.4 cm, respectively. Likewise, the head depth and width are 20.0 cm and 15.1 cm.

The two-meter box and phantom geometries were chosen for this analysis because of the extensive data base of measurements and calculations previously compiled for theses geometries in a prompt radiation environment. Figure 2 depicts an isometric view of the combinatorial geometry model of the phantom standing in the two-meter box.

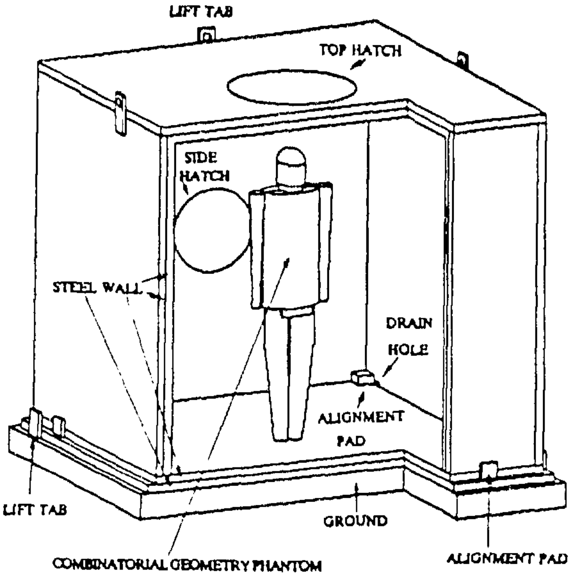

Figure 2. Isometric View of the MASH Geometry Model of the Combinatorial Geometry Phantom Standing Inside the Two-Meter Box Test Bed.

B. Fluence Spectra Analysis

A sampling of the fluence spectra results are given in Figure 3 for the two-meter box, and in Figure 4 for the mid-gut position of the phantom standing in the two-meter box. In the figures, each of the fluence spectra are normalized to the total fluence for that particular spectra, and for clarity, the spectra for the 24 hour and 72 hour sources are offset by the ratio of their total to the 4 hour source total. Therefore, only spectral shapes are indicated in the figures without reference to absolute magnitudes.

The most important result obtained from the spectral data comparisons is the similarity in spectral shape between the ^{60}Co source and the fallout sources at the different time steps after transport into the target assembly. If the nomailzation offsets were removed from Figures 3 and 4, the four curves presented would virtually be indistinguishable. This indicates that a ^{60}Co source would probably be a good first order approximation to a tactical fission weapon fallout source once transported through the environment into the armored vehicle. Similar spectra results (with the exception of the ^{60}Co source interval) were seen for the free-field and phantom standing in the free-field.

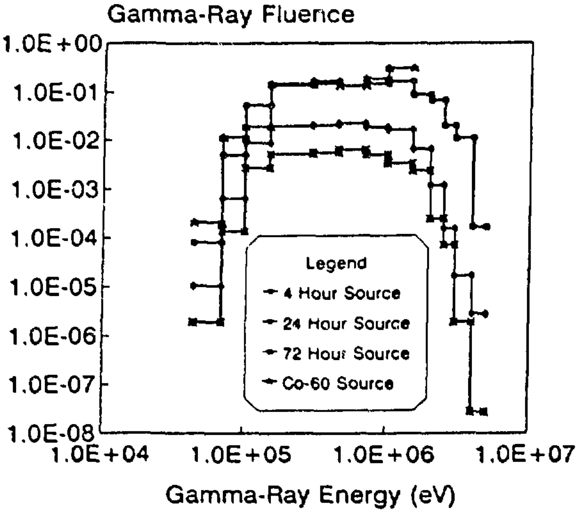

Figure 3. Gamma-Ray Fluence Spectra for the Center of the Two-Meter Box as a Function of a Dispersed Radiation Source Uniformly Distributed in a 1000 Meter Radius Area.

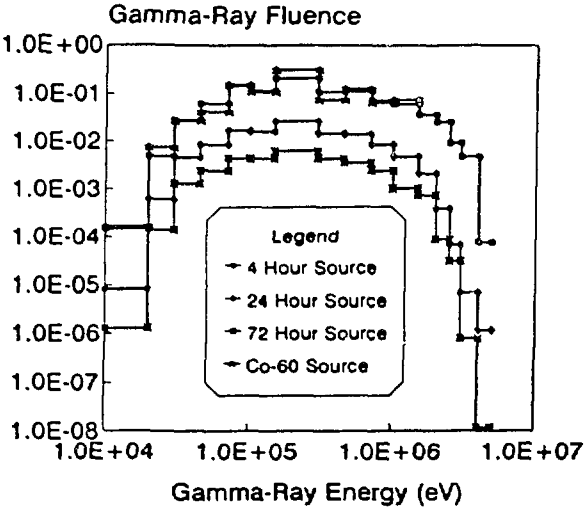

Figure 4. Gamma-Ray Fluence Spectra for the Phantom (Mid-Gut) Standing in the Two-Meter Box as a Function of a Dispered Radiation Source Uniformly Distributed in a 1000 meter Radius Area.

C. Protection Factor Analysis

The gamma-ray protection factor (GPF) results for both the ^{60}Co dispersed radiation source and the fallout radiation source are presented in Table 1 for fluence and Table 2 for free-in-air tissue dose. The GPF is defined as the ratio of the free-field gamma-ray fluence (or dose) divided by the shielded structure gamma-ray fluence (or dose). In both tables, the gamma-ray protection factors for the prompt radiation environment at the NATO standard 400 meter test site at the APRF are included for comparison purposes.

The results indicate substantial radiation protection factors for the ^{60}Co dispersed radiation source and the fallout sources compared to the prompt radiation protection factors. Fluence protection factors range from 40 to 182 for the two-meter box and from 25 to 128 for the mid-gut position of the phantom standing in the box. The fluence protection factors for the phantom standing in the free-field were essentially one and were independent of the source. The dose protection factors ranged from 40 to 95 for the two-meter box and from 55 to 123 for the mid-gut position of the phantom standing in the box. The GPFs for the mid-gut position of the phantom standing in the free-field indicate approximately a 50% increase in protection and again appear to be independent of the source. One point worth noting is the comparison of the GPFs for the ^{60}Co source and the 4 hour fallout source. The fluence protection factors (Table 1) indicate approximately a 70% difference, however, the dose GPFs (Table 2) indicate virtually no differences. This result could imply a ^{60}Co source would be a good first order approximation for a tactical fission weapon fallout protection factor analysis. Further studies would be necessary before this proposition could be adopted.

Table 1. Fluence Gamma-Ray Protection Factors for the Target Geometries Analyzed in the Application of MASH 1.0 to Radiological Warfare Weapons.

Source	2m Box	Phantom MG	Phantom MG in 2m Box
^{60}Co	37.9	1.02	25.7
4 Hour	68.5	1.03	50.4
24 Hour	156	1.05	109
72 Hour	182	1.07	128
APRF @ 400m	6.92	0.73	2.47

Table 2. Free-In-Air Tissue Dose Gamma-Ray Protection Factors for the Target Geometries Analyzed in the Application of MASH 1.0 to Radiological Warfare Weapons.

Source	2m Box	Phantom MG	Phantom MG in 2m Box
^{60}Co	40.3	1.53	56.9
4 Hour	40.1	1.54	54.5
24 Hour	87.6	1.58	114
72 Hour	95.3	1.59	123
APRF @ 400m	3.53	0.70	1.56

IV. CONCLUSIONS AND RECOMMENDATIONS

MASH has been successfully applied to analysis of dispersed radiation sources and fallout sources from a nuclear weapon detonation. For this study, idealized uniformly distributed sources were analyzed for comparative purposes. A protection factor analysis for the two-meter box, the phantom standing in the free-field, and the phantom standing in the two-meter box were performed utilizing the source characterization parameters resulting from the optimization study. The protection factor analysis indicated significant free-in-air tissue dose gamma-ray protection factors ranging from 40 to 123 for the two-meter box with an [illegible]thout the phantom standing inside. These factors range from a factor of 10 to 80 times larger than the protection factors due to prompt radiation for the same geometries.

The capabilities of MASH for fallout or dispersed radiation analysis were determined from this preliminary investigation and parameter optimization study. With a link to a fallout or dispersed radiation source characterization program, MASH can be utilized for analysis of armored vehicles in dispersed radiation environments. This coupling would also allow for environmental effects (e.g. wind direction, rain, etc.) to be incorporated into the source description. This would provide the vehicle designers, combat modelers, and battlefield commander with the capability to assess an armored vehicles vulnerability/survivability to the prompt radiation and residual radiation utilizing the same code system.

A point worth future consideration is the analysis of dispersed and fallout radiation sources on the surface of the armored vehicle or shielded structure. An armored vehicle moving through or positioned in a contaminated radiation environment will collect a thin layer of radioactive debris on the surface of the vehicle. MASH should be modified to include the capability of calculating the effects of this radiation on crew and electronics. This analysis would require a coupling of the adjoint Monte Carlo calculation with the forward discrete ordinates calculation directly on the surface of the armored vehicle or structure.

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