RADIATION DOSE DEPOSITION IN THE ACTIVE MARROW OF REFERENCE MAN

Science Applications, Inc.
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Radiation Dose Deposition in the Active Marrow of Reference Man

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Radiation Transport in Man Neutron
Reference Man Gamma Ray
Bone Marrow MORSE Computer Code
Radiation Dose Combinatorial Geometry

Dose Deposition in the active bone marrow of reference man was calculated using the MORSE Monte Carlo transport Code in the adjoint mode. Calculations were made in a three region reference man phantom described in Combinatorial Geometry. Calculations were performed using cross sections and KERMA factors from the 37 neutron-21 gamma ray group DNA Few Group Library. KERMA factors used in the calculation of dose were those for the constituents of active marrow alone for neutron dose and active marrow...
19. KEY WORDS (Continued)

DNA Few Group Library
KERMA Factor
Cross Section
Adjoint Radiation Transport

20. ABSTRACT (Continued)

plus trabecular bone constituents for photon dose. Dose deposition (or response) functions (rad (marrow) per unit incident radiation fluence) are tabulated in energy differential and angle integral and differential form for gamma ray dose from incident gamma rays and for neutron and gamma ray dose from incident neutrons. Tabulations are for eight skeletal regions and for reference man. The dose deposition factors have been used to determine marrow dose from hypothetical contemporary weapon types and for Little Boy and Fat Man.
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SECTION I
INTRODUCTION

This report presents the method and results of calculations of human marrow dose deposition from energy and angular-differential neutron and gamma ray fluences incident on the human body. Marrow dose is of interest due to its apparent relationship to the early mortality effect in mammals, subsequent to their exposure to radiation of the type produced by nuclear weapon detonations and other sources. A comprehensive review of this effect has been performed as part of the Reactor Safety Study (1). According to references cited in that study: "It is generally believed that damage to the bone marrow is the most important contributor to early death from large doses to the whole body. That is, radiation damage to the lung or to the gastrointestinal tract is not likely to be lethal unless accompanied by bone marrow damage." Thus, dose to the bone marrow is considered to be crucial in determining mortality probability in a subject who has suffered marrow, lung, gastrointestinal tract and other damage as a result of whole body exposure to an external radiation source. The effects of such damage are collectively referred to as the acute marrow syndrome and can produce death within 30 to 60 days subsequent to a single, short-duration exposure in the range of a few to several hundred rads (tis) free-in-air (FIA).

Accident, clinical and atomic bomb survivor data have been used to estimate the dose-effect relationship for death resulting from the acute marrow syndrome. The relationship is depicted in Figure I-1 for the cases of minimal, supportive and heroic post-exposure medical care. Minimal care may be taken to mean the treatment of symptoms and maintenance of patient comfort; supportive care includes the use of antibiotics to bolster the body's defenses against infection, and heroic care refers to such extremes
as bone marrow transplants. Most available data is relevant to the minimal care case. Therefore, the marrow dose required for a 50% probability of death (LD$_{50}$) in such cases, which has a value of 340 rad (marrow), may be used with high confidence to an accuracy of $\pm 10\%$. It should be noted, however, that confidence in such accuracy applies only to instances of whole body irradiation with low LET$^1$ radiation; i.e., the same type which forms the basis for the above dose-mortality criterion.

Neutrons, which deposit their energy mainly through the production of heavy, charged (high LET) particles have been shown to be more effective in producing biological damage per unit dose deposition than are low LET particles. In one experiment (2) involving the comparison of the response of dogs to gamma rays and mixed gamma ray-fission neutron exposure, the relative biological effectiveness (RBE) per unit marrow dose between neutrons and gamma rays in producing death was estimated as 1.4. However, other studies have shown such RBE's for various types of tissue cell damage to be dependent both on neutron fluence intensity and energy spectrum. Specifically, studies by Katz, et al., (3) indicate that for doses in excess of 100 rad (marrow) the RBE for reproductive incapacitation of mouse marrow cells is 4 and 3 for 0.43 MeV and 1.5 MeV neutrons respectively and that these RBE values rise exponentially with decreasing dose below 100 rad (marrow). Because of this potential for increased biological effectiveness per unit dose of neutrons over that of gamma rays, neutron dose and neutron-induced gamma ray dose to the marrow are tabulated separately in this report.

$^1$Linear energy transfer (LET) is a measure of the rate of energy loss along the track of an ionizing particle, expressed in units of energy per unit track length (thousands of electron volts per micron). Low-LET radiation includes beta particles and gamma rays; high-LET radiation includes alpha particles and protons and, hence, particles such as neutrons which are likely to produce them.
Figure I-1

Estimated dose-response curves for 50% mortality in 60 days with minimal treatment (curve A), supportive treatment (curve B), and heroic treatment (curve C).
The balance of this report is written in four major sections, plus references, and appendices, which mainly contain tabulations of calculated data. Of the major sections the first contains a brief description of the radiation transport computation technique and computer code, a discussion of the origin and preparation of the multigroup radiation reaction cross sections and energy deposition factors, a description of the man phantom model, and the development of a rationale for and definition of human active marrow dosimetry for incident neutron and gamma radiation. The second major section describes the energy and angular differential results of the radiation transport calculations in terms of marrow dose (rad (marrow)) per unit incident fluence. The third presents integral marrow doses calculated for exposure to radiation from typical tactical weapon types and yields, as well as for the Little Boy and Fat Man devices. The final substantive section of this report contains a summary of major study findings and attempts to place these findings in perspective, especially with regard to the prediction of mortality probability from the acute marrow syndrome.
The marrow dose calculations have been performed using the radiation transport code MORSE (4,5). MORSE (Multigroup Oak Ridge Stochastic Experiment) is a multigroup neutron and gamma ray transport Monte Carlo code that may be used to solve coupled neutron-gamma ray problems in either the forward or adjoint mode.

Monte Carlo calculations in the forward mode may be likened to an analytical radiation transport experiment conducted according to the rules of the Boltzmann equation, in which a neutron or gamma ray is started at some source location, according to a predetermined energy distribution, followed through interactions with the surrounding media until it arrives in an energy-degraded state at the detector volume of interest and is scored as contributing to the energy deposition (dose) in that volume according to the energy of the radiation and the nature of the detector material. Calculations in the adjoint mode may be thought of as proceeding in the reverse order, with radiation particles started in the detector according to the energy distribution of the detector response, effectively gaining energy through interactions with surrounding media, and being scored as they enter a source region of interest. In the MORSE code this is accomplished for a coupled neutron-gamma ray transport problem by inverting the group-to-group transfer matrix. In such an inverted matrix neutrons and gamma rays may be thought of as gaining instead of losing energy, and gamma rays effectively produce secondary neutrons.
The advantage of the adjoint process lies in its efficiency in treating a finite number of localized detector regions receiving dose from a distributed external radiation source. If the source region is defined as that outside a simply defined surface (usually a sphere) about the detector and its immediate surroundings, the record of particles escaping through that surface away from the detector (the adjoint fluence) represents the dose deposition characteristics (response) of the detector weighted by the transport properties of the surrounding media. Thus, a fluence incident on the exterior of the surface may be scored according to the characteristics of the adjoint fluence to obtain the dose at the detector. In an adjoint calculation parameters usually recorded at the coupling surface are particle type, energy and direction cosine. Because of the difficulty in obtaining good statistics in such a problem, the location of the exit point on the surface is usually not recorded. Thus, a condition for the use of the adjoint results is that the fluence be uniform in its energy and angular dependence over all cross sections of the coupling surface.
THE CROSS SECTIONS AND KERMA FACTORS

Cross sections used in the calculations were taken from the Defense Nuclear Agency (DNA) Few Group Coupled Neutron-Gamma Ray Cross Section Library (6). The library was prepared for general use by ORNL using the AMPX code (7) and is derived from cross section data contained in the DNA Working Cross Section Library (8) and the Evaluated Nuclear Data File (ENDF) (9). The origin of data for each element in that library is given in Table II-1.

The cross sections were used in the 37 neutron group--21 gamma ray group structure provided by the library. Energy boundaries for this group structure are given in Table II-2. Cross section data were processed into this group structure using a $1/E$ weighting spectrum for all neutron groups except the thermal group, for which a 300°K Maxwellian weighting spectrum was used. The thermal cross section for hydrogen has been adjusted to account for its bound state in water. Scattering angular dependence is provided by coefficients of a $P_3$ Legendre expansion.

Dose deposition was determined using Kinetic Energy Released in Material (KERMA) factors calculated with the MACK code (10) and based on the same ENDF format data as are the multigroup cross sections. These KERMA factors are provided as part of the DNA Few Group Library, which contains multigroup KERMA values for a number of simple and compound materials as given in Table II-3.

In reviewing the published KERMA values, it was found that those for thermal neutrons (Grp 37) were not consistent with the cross section values for that group, being larger by a factor of 11.74 than KERMA calculated by hand directly from the cross sections. This problem was discussed with the authors of the DNA Few Group Library, and it was determined that they had produced the KERMA
using a straight $1/E$ weighting instead of the 300°K Maxwellian used to produce the cross section values. KERMA values used in this project for materials listed in Table II-3 have been adjusted to account for the Maxwellian weighting of the thermal group.
Table II-1  Data Description for the Defense Nuclear Agency
Few-Group Cross-Section Library

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<td>4169-1</td>
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<td>Li-6</td>
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<td>1974</td>
<td></td>
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<td>Battat, LaBauve - LASL</td>
<td>1974</td>
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<td>Be-9</td>
<td>Howerton, Perkins - LL</td>
<td>1973</td>
<td>4154-3</td>
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<td>B-10</td>
<td>LaBauve, Young, Hale - LASL</td>
<td>1972</td>
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<td>1973</td>
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*Secondary gamma-ray production cross sections processed with POPOP4.
**Not officially in ENDF/B-IV
Table II-2  NEUTRON AND GAMMA-RAY ENERGY BOUNDARIES FOR THE 37-21 COUPLED NEUTRON-GAMA LIBRARY

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*Read as 1.96x10^7.*
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<td>Gamma Free-in-Air Tissue Kerma</td>
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<tr>
<td>Gamma Ionization in Silicon</td>
<td>Rads/Si/(Photon/cm$^2$)</td>
</tr>
<tr>
<td>Snyder-Auxier Neutron Tissue Kerma</td>
<td>Rads/(Neutron/cm$^2$)</td>
</tr>
<tr>
<td>Clai borne-Trubey Gamma Tissue Dose</td>
<td>Rads/(Photon/cm$^2$)</td>
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<td>(Rads/Atom)/(Neutron/(cm$^2$·g))</td>
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<tr>
<td>C Neutron Kerma</td>
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<tr>
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<td>(Rads/Atom)/(Neutron/(cm$^2$·g))</td>
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<td>Si Gamma Kerma</td>
<td>(Rads/Atom)/(Photon/(cm$^2$·g))</td>
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<tr>
<td>Fe Gamma Kerma</td>
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<td>Snyder-Auxier Neutron Tissue Dose</td>
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THE MAN PHANTOM

The man phantom used as the radiation transport model in the calculation is based on that described by Snyder et al. (11). That phantom has been compared to the specifications for reference adult man as reported in ICRP 23, Report of the Task Group on Reference Man (12), and found to be very similar. A detailed comparison is given in Table II-4. The external surface configuration of the phantom is shown in Figure II-1. Internal detail includes skeleton and lungs only, the remainder being homogenized to a single uniform soft tissue material. Elemental compositions (% by weight) of tissues for these three regions are given in Table II-5.

The external and internal configurations of the phantom as described by Snyder et. al. were translated into combinatorial geometry suitable for use with the MORSE Code. The mathematical prescriptions for these details are given in Appendix A of this report. The combinatorial geometry phantom was tested to insure that all component placement was as desired and that no undefined regions existed. Testing was done using the PICTURE module of MORSE in the course of which a number cross sectioned views of the phantom were produced. These are presented in Figure II-2 through II-10.

The numeric and alphabetic code by which the various body regions of the phantom may be identified is identical for all 9 figures and is given on the following page.
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<tr>
<td>3</td>
<td>Soft Tissue, Legs</td>
</tr>
<tr>
<td>4</td>
<td>Soft Tissue, Genitals</td>
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<td>Lung Tissue, Left Lung</td>
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<td>6</td>
<td>Lung Tissue, Right Lung</td>
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<td>7</td>
<td>Skeletal Tissue, Spine and Skull</td>
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<td>Skeletal Tissue, Arms</td>
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<td>Skeletal Tissue, Legs</td>
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<td>Skeletal Tissue, Pelvis</td>
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<td>B</td>
<td>Skeletal Tissue, Ribs</td>
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<td>C</td>
<td>Skeletal Tissue, Clavicles</td>
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<tr>
<td>D</td>
<td>Skeletal Tissue, Scapulae</td>
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<td>E</td>
<td>Volume External to the Phantom</td>
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Table II-4  Body Organ Specifications for the MIRD (Snyder) Phantom and those from the Reference Man Report

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<td>45.13 wall; 200 contents</td>
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<td>Gastrointestinal tract</td>
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</tr>
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<td>stomach</td>
<td>150 wall; 250 contents</td>
<td>150 wall; 246.9 contents</td>
</tr>
<tr>
<td>small intestine-contents</td>
<td>640 wall; 400 contents</td>
<td>1044 wall plus contents</td>
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<tr>
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<td>210 wall; 220 contents</td>
<td>109.2 wall; 220 contents</td>
</tr>
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<td>Kidneys (both)</td>
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<td>Liver</td>
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<td>1,809</td>
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<td>999.2</td>
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<td>respiratory lymph nodes</td>
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<td>48,480 (28,000 g suggested for muscle; 12,500 g for separable adipose tissue)</td>
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<td>Pancreas</td>
<td>100</td>
<td>60.27</td>
</tr>
<tr>
<td>Skeleton</td>
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<td>10,470</td>
</tr>
<tr>
<td>cancellous bone</td>
<td>1,000</td>
<td>1,000</td>
</tr>
<tr>
<td>cortical bone</td>
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<td>4,000</td>
</tr>
<tr>
<td>red bone marrow</td>
<td>1,500</td>
<td>1,500</td>
</tr>
<tr>
<td>yellow bone marrow</td>
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</tr>
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<td>Spleen</td>
<td>180</td>
<td>173.6</td>
</tr>
<tr>
<td>Testes</td>
<td>35</td>
<td>37.08</td>
</tr>
<tr>
<td>Thymus</td>
<td>20</td>
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<tr>
<td>Thyroid</td>
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<td>19.63</td>
</tr>
<tr>
<td>Uterus</td>
<td>80</td>
<td>65.4</td>
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<tr>
<td>Total body</td>
<td>70,000</td>
<td>69,880</td>
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Table II-5 Elemental Composition of Different Tissues of the Phantom
(% by weight)

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<tr>
<th>Element</th>
<th>Skeletal Tissue</th>
<th>Lung Tissue</th>
<th>Total Body Minus Skeleton and Lungs</th>
</tr>
</thead>
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<tr>
<td>H</td>
<td>7.04</td>
<td>10.21</td>
<td>10.47</td>
</tr>
<tr>
<td>C</td>
<td>22.79</td>
<td>10.01</td>
<td>23.02</td>
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<tr>
<td>N</td>
<td>3.87</td>
<td>2.80</td>
<td>2.34</td>
</tr>
<tr>
<td>O</td>
<td>48.56</td>
<td>75.96</td>
<td>63.21</td>
</tr>
<tr>
<td>Na</td>
<td>0.32</td>
<td>0.19</td>
<td>0.13</td>
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<tr>
<td>Mg</td>
<td>0.11</td>
<td>7.4 x 10^-3</td>
<td>0.015</td>
</tr>
<tr>
<td>P</td>
<td>6.94</td>
<td>0.081</td>
<td>0.24</td>
</tr>
<tr>
<td>S</td>
<td>0.17</td>
<td>0.23</td>
<td>0.22</td>
</tr>
<tr>
<td>Cl</td>
<td>0.14</td>
<td>0.27</td>
<td>0.14</td>
</tr>
<tr>
<td>K</td>
<td>0.15</td>
<td>0.20</td>
<td>0.21</td>
</tr>
<tr>
<td>Ca</td>
<td>9.91</td>
<td>7.0 x 10^-3</td>
<td>0</td>
</tr>
<tr>
<td>Fe</td>
<td>0</td>
<td>0.037</td>
<td>0</td>
</tr>
</tbody>
</table>

\( ^a \text{Density } 1.4862 \text{ g/cm}^3 \)

\( ^b \text{Density } 0.2958 \text{ g/cm}^3 \)

\( ^c \text{Density } 0.9869 \text{ g/cm}^3 \)
Fig. II-1  The adult human phantom.
Figure II-2 Reference Man Phantom In
Combinatorial Geometry In the
X-Z Plane at Y=0
Figure II-2 (continued)
Figure II-3 Reference Man Phantom In Combinatorial Geometry In the Y-Z Plane at X=0
Figure II-4 Reference Man Phantom in Combinatorial Geometry

In the X-Y Plane at Z=-2 (legs and genitals)
Figure II-5 Reference Man Phantom In Combinatorial Geometry
In the X-Y Plane at Z=0 (legs, trunk, arms, pelvis)
Figure II-7 Reference Man Phantom In Combinatorial Geometry
In the X-Y Plane at Z=44.0 (trunk, arm, rib, lung, spine)
Figure II-8 Reference Man Phantom In Combinatorial Geometry
In the X-Y Plane at Z= 59.1 (trunk, arm, scapula, lung, spine)
Figure 11-9 Reference Man Phantom in Combinatorial Geometry
In the X-Y Plane at Z=68.25 (trunk, arm, clavicle, spine)
THE DOSIMETRY

The objective of the calculations was to determine dose to bone marrow. More particularly, this has been limited to the active bone marrow, i.e., that portion of the marrow which supports the maintenance of blood cell levels within the body. Thus, the dosimetric regions within the body are those containing active (red) marrow. These regions are shown in Figure II-11, along with the fraction of marrow in each region. Specific locations of these regions of active marrow within the skeleton are given in Appendix A. The marrow is assumed to be uniformly distributed within the skeleton in these regions.

The skeleton is made up of cortical (hard) and trabecular (spongy) bone, red and yellow marrow, cartilage and periarticular tissue. For the purpose of radiation transport in skeletal regions the precise locations of all these individual constituents are not taken into account. However, for the purpose of dosimetry consideration must be given to the size and location of active marrow and surrounding regions in order to insure that conditions of local charged particle equilibrium required for dose calculations from KERMA factors are in fact met.

Dose is deposited in the marrow by heavy charged particles, predominately protons, produced by neutron interactions and by electrons produced by photon interactions. The range of protons in water, which approximates the slowing-down properties of marrow, varies from 1.29 mm at 10 MeV to 0.0247 mm at 1 MeV and decreases rapidly below that energy (13). Ranges for heavier species such as alpha particles are even less, while those for electrons are considerably more, being on the order of a few millimeters for a 1 MeV electron (14). As described in ICRP 23, the active marrow is contained within interspaces between a network of plates and bars which comprise trabecular bone. For an adult, these spaces range in diameter
from 0.1 to 1.0 mm. The local charged particle equilibrium region and hence the dosimetric material for neutron interactions was selected as the active marrow alone (Table II-6). This choice was based on the above figures which indicate that the charged particles generated by neutrons at most energies of interest have ranges on the order of or considerably less than the characteristic dimension of the marrow. This is an important choice since homogenizing marrow and trabecular bone would have resulted in more than a 10% reduction in the hydrogen fraction for dosimetric purposes.

For photon interactions the local charged particle equilibrium region and hence the dosimetric material was selected to be the entire trabecular bone--active marrow mass (Table II-6). This selection was based on the range of energetic electrons in marrow and trabecular bone material, which is considerably greater than the characteristic marrow dimensions. This is important because the combined material contains 20 times the weight fraction of calcium as does marrow alone, and photoelectrons from calcium are the primary contributors to photon dose below a few hundred keV photon energy. On the other hand, the range of calcium photoelectrons is not so great as to require inclusion of the cortical bone in the dosimetric material, although this omission will result in an underestimate of the marrow dose from low energy photons within a millimeter or so of the trabecular-cortical bone interface.

KERMA values for equilibrium regions postulated as being applicable to charged particles produced by neutrons and gamma rays are given in Tables II-7 and II-8, respectively. Free-In-Air (FIA) tissue KERMA values provided with the DNA library are included in these tables for comparison.
Table II-6

ELEMENTAL COMPOSITION OF DOSIMETRIC REGIONS OF THE PHANTOM

<table>
<thead>
<tr>
<th>Element</th>
<th>Red Marrow</th>
<th>Red Marrow &amp; Trabecular Bone</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mass (g)</td>
<td>Wt. % (1)</td>
</tr>
<tr>
<td>C</td>
<td>618.0</td>
<td>41.2</td>
</tr>
<tr>
<td>H</td>
<td>159.0</td>
<td>10.6</td>
</tr>
<tr>
<td>N</td>
<td>48.0</td>
<td>3.2</td>
</tr>
<tr>
<td>O</td>
<td>672.6</td>
<td>44.8</td>
</tr>
<tr>
<td>P</td>
<td>1.64</td>
<td>0.11</td>
</tr>
<tr>
<td>S</td>
<td>0.05</td>
<td>0.00</td>
</tr>
<tr>
<td>Na</td>
<td>0.66</td>
<td>0.04</td>
</tr>
<tr>
<td>Mg</td>
<td>0.04</td>
<td>0.00</td>
</tr>
<tr>
<td>Ca</td>
<td>3.28</td>
<td>0.22</td>
</tr>
</tbody>
</table>

TOTAL: 1503.27 100.17 1967.76 98.9
REFERENCE TOTAL: 1500.00 100.0 1987.6 100.0


(1) Tables 105 and 106.
(2) Table 108
Table II-7
Neutron KERMA (rad/unit fluence)

<table>
<thead>
<tr>
<th>Group</th>
<th>Upper Energy Boundary (MeV)</th>
<th>Neutron Red Marrow KERMA</th>
<th>Neutron Free-in-Air Tissue KERMA</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>19.6</td>
<td>7.185-09</td>
<td>7.00-09</td>
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<td>2</td>
<td>16.9</td>
<td>6.842-09</td>
<td>6.64-09</td>
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<td>3</td>
<td>14.9</td>
<td>6.625-09</td>
<td>6.43-09</td>
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<td>4</td>
<td>14.2</td>
<td>6.522-09</td>
<td>6.33-09</td>
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<td>13.8</td>
<td>6.406-09</td>
<td>6.19-09</td>
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<td>6</td>
<td>12.8</td>
<td>6.247-09</td>
<td>6.00-09</td>
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<td>5.915-09</td>
<td>5.86-09</td>
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<td>10.0</td>
<td>5.848-09</td>
<td>5.76-09</td>
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<td>5.454-09</td>
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<td>5.439-09</td>
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<td>4.66-09</td>
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<td>4.555-09</td>
<td>4.32-09</td>
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<td>4.504-09</td>
<td>4.26-09</td>
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<td>2.128-09</td>
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<td>1.321-09</td>
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<td>8.175-10</td>
<td>7.68-10</td>
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<td>3.02-10</td>
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<td>6.384-11</td>
<td>6.01-11</td>
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<td>1.12-12</td>
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<td>1.795-12</td>
<td>1.69-12</td>
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<tr>
<td>Group</td>
<td>Upper Energy Boundary (MeV)</td>
<td>Gamma ray marrow- Trabecular bone KERMA</td>
<td>Gamma Free-in-Air Tissue KERMA</td>
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<td>-----------------------------</td>
<td>------------------------------------------</td>
<td>-------------------------------</td>
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<td>2.09-09</td>
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<td>0.010</td>
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<td>5.22-10</td>
</tr>
<tr>
<td>Bone Group</td>
<td>Percentage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------------------------------</td>
<td>------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skull</td>
<td>13.1%</td>
<td></td>
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</tr>
<tr>
<td>Vertebrae</td>
<td>28.4%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ribs + Sternum</td>
<td>10.2%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scapulae</td>
<td>4.8%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head and Neck of Both Arms</td>
<td>1.9%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Both Clavicles</td>
<td>1.6%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head and Neck of Both Legs</td>
<td>3.8%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pelvis</td>
<td>36.2%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Total Amount of Red Bone Marrow: 1500 g

Fig. II-11 Idealized model of the skeleton for computer calculations (left) and a more realistic representation (right) with percentages of red bone marrow found in the shaded portions of the bones. Clavicles and scapulae not shown in phantom.
SECTION III
ACTIVE BONE MARROW DOSE DEPOSITION FACTOR
(RESPONSE FUNCTION) CALCULATION

Calculations of adjoint marrow dose deposition factors, or response functions as they are sometimes called, were performed using the MORSE code, DNA Few Group Cross Section Library, reference man phantom and dosimetry specifications as described in the previous section. Transport was followed in the adjoint mode from the marrow locations to a spherical coupling surface of radius 200 cm about a point on the axis of the phantom at the base of the trunk of the body. Separate dose deposition calculations were performed for eight marrow regions as follows:

<table>
<thead>
<tr>
<th>Region</th>
<th>Total Active Marrow Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Pelvis</td>
<td>0.362</td>
</tr>
<tr>
<td>2. Vertebrae (spine)</td>
<td>0.284</td>
</tr>
<tr>
<td>3. Skull</td>
<td>0.131</td>
</tr>
<tr>
<td>4. Ribs and Sternum</td>
<td>0.102</td>
</tr>
<tr>
<td>5. Scapulae</td>
<td>0.048</td>
</tr>
<tr>
<td>6. Legs</td>
<td>0.038</td>
</tr>
<tr>
<td>7. Arms</td>
<td>0.019</td>
</tr>
<tr>
<td>8. Clavicles</td>
<td>0.016</td>
</tr>
</tbody>
</table>

In each case advantage was taken of the bilateral symmetry of man, which allowed calculations to be performed for one side only and the results applied to components of both sides. To accomplish this, routines were written which uniformly distributed particle starting points over that portion of a given marrow component having positive X coordinates, i.e., that on the right side of the phantom.
Calculations were performed on a CDC7600 computer. Table III-1 presents some details of the Monte Carlo results. Separate calculations were performed for adjoint gamma ray and neutron transport so that the neutron-induced gamma ray portion of the dose could be isolated. Adjoint calculations of neutron starts had run times ranging from 94 seconds for the skull to 481 seconds for the spine. This range of run times indicates the sensitivity of the transport of neutrons of all energies to the amount of flesh surrounding the detector location, which is born out further by the number of scatterings recorded for transport from each region. The calculations in which only gamma rays were started have run times on the order of twice those for neutron starts. This is not due to the gamma transport but to that of the neutrons produced during the course of the calculation. In the adjoint sense the largest source of these neutrons in flesh material is gamma ray capture, particularly in hydrogen, the cross section for which is inversely proportional to neutron energy. Therefore, the adjoint gamma ray-induced neutrons have an initial energy spectrum heavily skewed to the lower energies. This results in the large number of scatters which require so much run time.

ANGLE-INTEGRATED RESULTS

Results of the active marrow dose deposition calculations were recorded in two forms. The first is a set of angle-integrated, energy-differential values applicable to the case of isotropic radiation fluence incidence on the coupling surface. These results are tabulated in detail for all eight marrow regions and for reference man in Appendix B of this report. Figures III-1 through III-10 present them in graphical form for reference man and for the four regions of the body (pelvis, spine, skull, ribs) which contain the highest fraction of active marrow, together possessing .879 of the total. Values for reference man were obtained by adding marrow fraction-weighted dose deposition factors for the eight red marrow
regions. For the purpose of gaining a qualitative understanding of the data presented in these figures, it should be noted that, of the four specific regions represented, two, the pelvis and spine, are deep within the body, while the other two, the skull and ribs, are shallow. Thus, the data graphically presented here for deep marrow regions may also be considered representative of those for the legs. Together, these deep marrow regions account for .684 of the total in the body. Likewise, results for the skull and ribs may be considered representative of the other shallow marrow in the body, which resides in the arms, scapulae and clavicles. Shallow marrow constitutes .316 of the total in the body.

Figures III-1 through III-5 contain angle-integrated gamma ray dose deposition ($\gamma-\gamma$) factors (rad (marrow) per unit gamma ray fluence) for 20 of the 21 gamma ray energy groups for which data were produced. Those data not included in the figures are for energies between 10 and 14 MeV and are consistent with values up to that energy. In comparison with tissue KERMA used to compute free-in-air dose (rad (tis)) the marrow dose deposition is lower by fairly consistent factors for both deep and shallow marrow, and hence for reference man, down to photon energies of a few hundred keV. Below that energy substantial differences occur between tissue KERMA and the marrow response and between the responses of deep and shallow marrow. These differences are caused by the attenuation of low energy photons in the body which more than counteracts the rise in KERMA due to the photoelectric effect. The result of this attenuation is less pronounced in the shallow marrow than in the deep marrow, which dominates the response for reference man.

The fractional standard deviation (FSD) of the calculated $\gamma-\gamma$ deposition results is summarized on the following page.
### γ-γ Dose Deposition FSD

<table>
<thead>
<tr>
<th>Gamma Ray Energy (MeV)</th>
<th>Shallow Marrow</th>
<th>Deep Marrow</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.0 to 0.7</td>
<td>&lt; .05</td>
<td>&lt; .050</td>
</tr>
<tr>
<td>0.7 to 0.03</td>
<td>&lt; .05</td>
<td>&lt; .075</td>
</tr>
<tr>
<td>0.03 to 0.02</td>
<td>&lt; .10</td>
<td>&gt; .20</td>
</tr>
<tr>
<td>0.02 to 0.01</td>
<td>&lt; .50</td>
<td>No Data</td>
</tr>
</tbody>
</table>

The lack of data for dose deposition in the deep marrow for the lowest energy photons indicates all such photons followed from that marrow in the adjoint mode upscattered before exiting the phantom. Conversely it should follow that such photons incident on the phantom are virtually incapable of penetrating to the deep marrow.

Figures III-6 through III-10 present the angle-integrated partial dose deposition factors for active marrow for incident neutrons in 37 energy groups. These data are coplotted with neutron tissue KERMA free-in-air. The portion of the active marrow dose deposited by incident neutrons as depicted in these figures is limited to that resulting from energy deposition by neutron-induced heavy charged particles and is hereafter referred to as the n-n dose component. The FSD values of the calculated n-n deposition results are summarized below:

### n-n Dose Deposition FSD

<table>
<thead>
<tr>
<th>Neutron Energy (MeV)</th>
<th>Shallow Marrow</th>
<th>Deep Marrow</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.6 to 4.97</td>
<td>&lt; .05</td>
<td></td>
</tr>
<tr>
<td>4.97 to 0.111</td>
<td>&lt; .10</td>
<td></td>
</tr>
<tr>
<td>0.111 to 3.35-3</td>
<td>&lt; .20</td>
<td></td>
</tr>
<tr>
<td>3.35-3 to 4.14-7</td>
<td>&gt; .20</td>
<td></td>
</tr>
<tr>
<td>Thermal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>19.6 to 7.41</td>
<td></td>
<td>&lt; .05</td>
</tr>
<tr>
<td>7.41 to 2.31</td>
<td>&lt; .10</td>
<td></td>
</tr>
<tr>
<td>2.31 to 0.55</td>
<td>&lt; .15</td>
<td></td>
</tr>
<tr>
<td>0.55 to 4.14-7</td>
<td>&gt; .20</td>
<td></td>
</tr>
<tr>
<td>Thermal</td>
<td></td>
<td>&lt; .20</td>
</tr>
</tbody>
</table>

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As can be seen from these FSD values and from the apparent fluctuation in n-n deposition factors depicted in the figures, the statistical variation in these values for deep marrow below about 0.1 MeV and for shallow marrow below 0.001 MeV is very large for the individual marrow components. This is particularly true of the deep marrow. Fortunately, the dose contribution in this energy range from transported weapon neutrons is relatively small. Thus, in spite of the large statistical variance in the low energy data the total dose from such neutrons is usually statistically reliable to within 14% or better, as discussed in the summary section of this report. Also fortunately, the reference man weighted-average n-n response as depicted in Figure III-6 shows a reasonable degree of consistency over this low energy region. As such, it is used as the basis for the succeeding discussion of the n-n dose deposition component.

The n-n deposition is strongly dependent on incident neutron energy above approximately several keV. Between 20 MeV and a few 10's of keV the value for this dose component drops two orders of magnitude. Relative to the value of tissue KERMA over the same energy range, the drop is from about 0.7 rad (marrow) per rad (tissue, FIA) to about 0.1. Below this energy range the marrow dose deposition of incident neutrons continues to decrease, but less rapidly than does the tissue KERMA function. This results in equality between the two in the vicinity of a few keV. At energies below this, the n-n deposition is nearly constant with energy, while the tissue KERMA drops another order of magnitude before being enhanced at energies near thermal by the contribution of the (n,p) reaction in nitrogen. It is the contribution of this reaction in marrow which causes the constancy of the n-n deposition component below a few keV. Incident neutrons in this energy range deposit what little energy they possess by proton recoil, then distribute themselves such that a fraction are captured in the marrow, thereby contributing 626 keV per reaction to the deposited dose. This fraction apparently changes little until
the incident neutron possess energies at or near thermal, at which they can no longer penetrate sufficient distances in the body to reach the bulk of the marrow.

Figures III-11 through III-15 present the total dose deposition for incident neutrons and that component due exclusively to neutron-induced gamma rays produced within the body in comparison with neutron tissue KERMA used to compute free-in-air tissue dose (rad (tis)). The difference between the total dose deposition and neutron-induced gamma deposition is that which is due exclusively to neutrons. It can be seen from these figures that the neutron-induced gamma ray component (referred to hereafter as n-γ deposition) forms a floor upon which rests the remainder of the neutron marrow dose deposition energy dependence. Unlike the neutron tissue KERMA shown for comparison, this floor has virtually no dependence on neutron energy. In fact, the n-γ component is so uniform over the entire neutron energy range that the resulting dose may be considered to depend on neutron number fluence only. For deep marrow, which constitutes the majority of that in reference man, this fluence-dose conversion is approximately $1.6 \times 10^{10}$ rad (marrow) per unit neutron fluence, while for shallow marrow the dose deposition is approximately 85% of this value. Exceptions to this occur at neutron energies greater than about 6 MeV and those about thermal. The former exception can be explained by the additional contribution above this energy of substantial amounts of inelastic scatter gamma ray production. The reason for the latter is a bit more difficult to pinpoint. However, it is probably due to geometry considerations. Very low energy neutrons are not able to penetrate into the body past more than the very shallowest marrow. Therefore, about half the photons produced by these neutrons will exit the body without having to pass through any but a small amount of marrow. Thus, as might be expected, the n-γ dose deposition for thermal neutrons incident on reference man is about half that for more energetic neutrons.
The fractional standard deviation (FSD) of the calculated n-γ deposition results is summarized below:

<table>
<thead>
<tr>
<th>Neutron Energy (MeV)</th>
<th>Shallow Marrow</th>
<th>Deep Marrow</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.6 to 8.99</td>
<td>&lt; .12</td>
<td>&lt; .10</td>
</tr>
<tr>
<td>8.19 to 5.25-2</td>
<td>&lt; .20</td>
<td>&lt; .15</td>
</tr>
<tr>
<td>5.25-2 to 2.90-5</td>
<td>&lt; .20</td>
<td>&lt; .20</td>
</tr>
<tr>
<td>2.90-5 to 4.14-7</td>
<td>&lt; .30</td>
<td>&lt; .35</td>
</tr>
<tr>
<td>Thermal</td>
<td>~ .11</td>
<td>~ .11</td>
</tr>
</tbody>
</table>

The poorer shallow marrow FSD figures for high energy neutrons result from increased neutron leakage at lower neutron energies and the increased leakage of high energy photons from which adjoint neutrons of high energy might originate directly.

As previously noted, the total dose deposited by incident neutrons consists of the sum of the n-n and n-γ components. The statistical variation of this total is a composite of those for the two components. FSD values for the n-n component dominate this composite for neutron energies above a few hundred keV, while those for the n-γ component dominate below this energy range. The result is that for typical transported weapon neutron spectra the predicted statistical variance of the calculated total marrow dose deposited by incident neutrons is 16% or better.
Table III-1
Monte Carlo Details of Active Marrow Dose Calculation

<table>
<thead>
<tr>
<th>Calculation</th>
<th>Histories</th>
<th>Run Time (sec)</th>
<th>Scatterings</th>
<th>Secondaries Generated</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>γ and n-γ</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pelvis</td>
<td>16,000</td>
<td>846</td>
<td>175,861</td>
<td>23,096</td>
</tr>
<tr>
<td>Spine</td>
<td>16,000</td>
<td>978</td>
<td>170,159</td>
<td>22,416</td>
</tr>
<tr>
<td>Skull</td>
<td>16,000</td>
<td>202</td>
<td>68,762</td>
<td>13,470</td>
</tr>
<tr>
<td>Ribs &amp; Sternum</td>
<td>16,000</td>
<td>778</td>
<td>111,048</td>
<td>15,850</td>
</tr>
<tr>
<td>Scapulae</td>
<td>16,000</td>
<td>619</td>
<td>87,479</td>
<td>14,658</td>
</tr>
<tr>
<td>Legs</td>
<td>16,000</td>
<td>283</td>
<td>146,512</td>
<td>22,337</td>
</tr>
<tr>
<td>Arms</td>
<td>16,000</td>
<td>441</td>
<td>60,805</td>
<td>13,946</td>
</tr>
<tr>
<td>Clavicles</td>
<td>16,000</td>
<td>570</td>
<td>88,238</td>
<td>14,783</td>
</tr>
<tr>
<td><strong>n-n</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pelvis</td>
<td>16,000</td>
<td>388</td>
<td>76,491</td>
<td>None</td>
</tr>
<tr>
<td>Spine</td>
<td>16,000</td>
<td>442</td>
<td>72,327</td>
<td></td>
</tr>
<tr>
<td>Skull</td>
<td>16,000</td>
<td>105</td>
<td>37,158</td>
<td></td>
</tr>
<tr>
<td>Ribs &amp; Sternum</td>
<td>16,000</td>
<td>404</td>
<td>45,806</td>
<td></td>
</tr>
<tr>
<td>Scapulae</td>
<td>16,000</td>
<td>344</td>
<td>42,252</td>
<td></td>
</tr>
<tr>
<td>Legs</td>
<td>16,000</td>
<td>124</td>
<td>71,334</td>
<td></td>
</tr>
<tr>
<td>Arms</td>
<td>16,000</td>
<td>271</td>
<td>38,165</td>
<td></td>
</tr>
<tr>
<td>Clavicles</td>
<td>16,000</td>
<td>325</td>
<td>42,140</td>
<td></td>
</tr>
</tbody>
</table>
Figure III-1  Dose Deposition Per Unit Gamma Ray Fluence
Tissue Kerma Free-in-Air (——) rad (tis)
Reference Man Active Marrow (——) rad (red marrow-trabecular bone)
Figure III-3 Dose Deposition Per Unit Gamma Ray Fluence
Tissue Kerma Free-in-Air (---) rad (tis)
Spine Active Marrow (-Θ--) rad (rad marrow-trabecular bone)
Figure III-4 Dose Deposition Per Unit Gamma Ray Fluence
Tissue Kerma Free-in-Air (-----) rad (tis)
Skull Active Marrow (---) (red marrow-trabecular bone)
Figure III-5 Dose Deposition Per Unit Gamma Ray Fluence
Tissue Kerma Free-in-Air (---) rad (tis)
Rib Active Marrow (---) (red marrow-trabecular bone)
Figure III-6 Dose Deposition per unit neutron fluence
Tissue Kerma free-in-air (---) rad (tis)
Reference Man Active Marrow, n-n (---) rad (red marrow)
Figure III-8 Dose Deposition per Unit Neutron fluence

- Tissue Kerma free-in-air (—) rad (tis)
- Spine Active Marrow, n-n (○) rad (red marrow)
Figure 3. Dose Deposition per unit neutron fluence.

- Tissue Kerma free-air (n-air)
- Skull Active Marrow, n-air

10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12} Rad (per unit neutron fluence)

10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} Neutron Energy (MeV)
Figure III-11  Dose Deposition per unit neutron fluence
Tissue Kerma free-in-air (---) rad (tis)
Reference Man Active Marrow, Total (○) rad (red marrow)
N-γ (Δ) rad (red marrow)
Figure III-12 Dose Deposition per Unit Neutron fluence
Tissue Kerma free-in-air (---) rad (tis)
Pelvis Active Marrow, Total (O---) rad (red marrow)
N-\gamma (---\bigtriangleup--) rad (red marrow)
ANGLE DIFFERENTIAL RESULTS

Results of the dose deposition calculations are tabulated in Appendix C as adjoint exit fluences in twelve equal solid angle bins and in five polar angle bands averaged over azimuth. The orientation of these bins relative to the reference man phantom is shown in Figure III-16. The azimuthal averaged values are presented for reference man as a whole. The binned values pertain to active marrow located on the right (positive X) side of the phantom only and are presented for reference man and for all eight marrow regions. To obtain the angular differential dose deposition factors for marrow located on the left (negative X) side of the phantom, the recorded azimuthal response values must be transposed across the Y-Z plane. The dose deposition for the total marrow (positive and negative X) of any body region in a particular azimuth angle bin is the average of the calculated and transposed value for that bin. From Figure III-15 it can be seen that this procedure will apply to three pairs of azimuthal bins, 2 and 3, 5 and 7, and 9 and 10.

Figures III-17 through III-22 depict angular differential dose deposition factors (adjoint exit fluence) for neutrons and gamma rays in several representative energy groups. Data are presented for polar angle dependence with azimuthal symmetry and azimuthal dependence in polar angle band C, corresponding to the midplane of the reference man phantom. Cosine values pertain to adjoint exit fluence directions, as shown in Figure III-16. These are in opposition to the directions of the corresponding incident fluences, the true orientation of which are given in parentheses. A-P refers to the direction from phantom anterior to phantom posterior or frontal exposure to an incident fluence. P-A refers to the opposite of this.
Polar angle dependencies for all modes of dose deposition are similar in that incident radiation in the upward or downward direction is less effective at depositing dose in the marrow than is that from other directions, particularly at and just above the phantom midplane. This effect increases with decreasing radiation energy and is most pronounced for incident neutrons.

Azimuthal angle dependencies are similar for gamma ray and neutron (n-n) dose deposition. Both radiation types are more effective at depositing dose in the case of posterior incidence on the phantom than for other angles. This effect also increases with decreasing radiation energy and is more pronounced for incident neutrons. Neutron induced gamma ray (n-γ) deposition favors both posterior and anterior incidence over that from the side, with posterior gaining ascendency only at low neutron energies.

The angular dependencies noted above are a direct result of the location of the marrow, which is predominately deep in the trunk of the body but not symmetric about its centerline. These data are the most differential recorded for these calculations and therefore exhibit the worst statistical variance. However, there is a consistency in the angular dependent behavior of all three response types which extends over the entire energy ranges considered, the general nature of which is described above. There are of course some deviations from such consistent behavior trends. Such deviations are exhibited by neutron dose deposition for incident neutrons in group 29 (1.23 to 3.35 keV). However, an examination of angular differential dose deposition for other neutron energies in the vicinity of that group indicates that this deviation is an isolated incidence. Though other such deviations do exist, the general consistency of the angular differential results would seem to show that they may be used together with angular differential fluence to obtain integral dose values which are more reliable than statistical variance alone would indicate.
Figure III-16  Solid Angle Bin Orientation for Adjoint Fluence Exit
(1.0472 steradians per bin)

Polar Orientation

<table>
<thead>
<tr>
<th>Polar Band</th>
<th>Cosine Boundaries</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.00 to .833</td>
</tr>
<tr>
<td>B</td>
<td>.833 to .333</td>
</tr>
<tr>
<td>C</td>
<td>.333 to -.333</td>
</tr>
<tr>
<td>D</td>
<td>-.333 to -.832</td>
</tr>
<tr>
<td>E</td>
<td>-.833 to -1.00</td>
</tr>
</tbody>
</table>

Azimuthal Orientation

[Diagram showing front (anterior) and back (posterior) with corresponding azimuthal bins and cosine boundaries]

Azimuthal Bins and Cosine Boundaries

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Figure III-17. Active Marrow Dose Deposition in Reference Man from Incident Gamma Rays in Five Polar Angle Bands as a Fraction of the 4π Angle-Integrated (isotropic) response.
Figure III-18. Active Marrow Dose Deposition In Reference Man from Incident Gamma Rays in Three Azimuthal Angle Bins in the Phantom Midplane as a fraction of the $4\pi$ Angle Integrated (isotropic) Response.
Legend

- Group 4, 13.8 to 14.2 MeV
- Group 13, 4.97 to 6.38 MeV
- Group 21, 0.55 to 1.11 MeV
- Group 29, 1.23 to 3.35 keV
- Group 37, Thermal

Figure III-19. Active Marrow Neutron Dose Deposition (n-n) in Reference Man from Incident Neutrons in Five Polar Angle Bands as a Fraction of the 4π Angle-Integrated (isotropic) n-n Response.
Figure III-20. Active Marrow Neutron Dose Deposition (n-n) in Reference Man from Incident Neutrons in Three Azimuthal Angle Bins in the Phantom Midplane as a Fraction of the 4π Angle-Integrated (isotropic) n-n Response
Figure III-21. Active Marrow Gamma Ray Dose Deposition in Reference Man from Incident Neutrons (n-γ) in Five Polar Angle Bands as a Fraction of the $4\pi$ Angle-Integrated (isotropic) n-γ Response
Figure III-22. Active Marrow Gamma Ray Dose Deposition in Reference Man from Incident Neutrons (n-γ) in Three Azimuthal Angle Bins in the Phantom Midplane as a Fraction of the 4π Angle-Integrated (isotropic) n-γ Response.
SECTION IV
MARROW DOSE FROM NUCLEAR WEAPONS RADIATION

Calculations were made to determine marrow dose in reference man produced by four hypothetical weapon types and two real weapons, according to the parameters given in Table IV-1. Calculations of radiation transport in air were performed using ATR4.1 (18,19) and include contributions from neutrons, neutron-induced gamma rays, prompt gamma rays and debris gamma rays.

Total dose (rad(tis), Free-In-Air) and neutron and gamma ray components are plotted versus ground range in Figures IV-1 through IV-3 for selected weapon types. Energy spectra for neutrons and gamma rays, excluding debris gamma rays, were also obtained from ATR4.1. These spectra apply to transport in infinite homogeneous air and have been normalized to provide the correct integrated Free-In-Air (FIA) dose values for the air-over-ground case. The infinite air spectra approximation was necessitated by the lack of any available alternative source of energy-differential fluence data which may be related to realistic weapon output spectra. A study conducted by E. A. Straker (20) has shown that the actual spectra at the air-ground interface tend to be somewhat more energetic than those computed for infinite air, due to the increased absorption of the low energy scattered component by the ground. This effect is most pronounced for bursts at or near ground level and becomes less so as the height of burst increases. A second approximation concerning the transported radiation fluence spectra involves the debris radiation. Spectra for this component were assumed to be the same as that for the combined prompt and air-secondary component. This approximation results in an overestimate of debris gamma ray energy. Finally, radiation fluences were assumed to be isotropic. In fact, however, the gamma ray fluence
is approximately 10 times greater in the direction away from the
burst than it is in the direction toward the burst. Available
calculations (21) for transport from a very low air burst (15.2 m
alt.) through 1200 m of air above the air-ground interface show
the thermal neutron fluence \((0 < E < 4.4 \times 10^{-7} \text{ MeV})\) to be somewhat
biased in the upward direction from the ground. Epithermal neutrons
\((4.14 \times 10^{-7} < E < .111 \text{ MeV})\) are virtually isotropic, while higher
energy neutrons exhibit a net fluence in the direction away from
the burst, which increases with neutron energy. For fission
weapon neutrons in the energy range \(.111 < E < 20 \text{ MeV}\), the average
ratio of fluence away from the burst to that toward it is a bit
less than 2 to 1, while for an enhanced device it is a bit more.
These high energy neutrons make up only 1/3 or less of the total
transported neutron fluence from a fission weapon while they account
for approximately 1/2 of that for an enhanced weapon. These approx-
imations should be kept in mind as one reads the following discus-
sion of the nature of weapon radiation deposition in human marrow.

Figures IV-4 through IV-8 present the average dose to the
active marrow as it compares to tissue dose FIA, total and compo-
nents, for the various weapons types identified in Table IV-1.
The nearly constant 45° slope exhibited by the data indicates that
little change takes place in the transported spectra of the radia-
tion components over the range of interest. Differences in total
marrow dose for various weapons at specific total dose FIA levels
(Figure IV-4) is more indicative of variations in neutron to
gamma ray free-in-air dose ratios than any other factor. This is
shown more dramatically in Figure IV-5 in which neutron marrow dose
is shown as it relates to total dose FIA. The World War II weapons
have very low neutron to gamma ray FIA dose ratios. Those for
enhanced radiation and other devices of the same yield are about
the same at equivalent total FIA dose levels, while those for the
low yield devices are highest of all. However, because of its large high energy neutron component, the fluence from the enhanced radiation device is more effective at depositing neutron dose in the marrow than other devices. This is shown by the fact that the neutron dose deposited by a given total exposure from such a device is as much as that produced by devices having higher neutron to gamma ray FIA dose ratios. It is further born out by the information presented in Figure IV-6, which indicates that neutrons from the enhanced device are the most efficient at producing neutron marrow dose, while those from the World War II devices, particularly Little Boy are the least efficient. This effect is mitigated somewhat by the efficiency with FIA neutron dose is converted to gamma ray dose in the marrow, as shown in Figure IV-7. Because neutron-induced gamma ray marrow dose is a function of incident number fluence and not of neutron energy, those devices possessing lower average neutron fluence energies are more efficient at producing such doses for a given FIA neutron dose level. This is exactly the reverse of the case for neutron marrow dose. As a result, the total dose FIA is virtually the same for nearly all the weapon types examined here. An exception to this is Little Boy, which possesses a transported neutron fluence component of very low average energy. These neutrons produce considerable dose by capture in nitrogen with its attendant 626 keV proton emission, while at the same time the number fluence to produce a given FIA dose level is so high that the neutron-induced gamma ray marrow dose per unit neutron dose FIA is approximately twice that for other devices. In sum then the transported neutron fluence from the Little Boy device is approximately half again as efficient at producing total marrow dose per unit neutron dose FIA as is the case for any other weapon. Finally, as shown in Figure IV-8, the gamma ray marrow dose produced per unit gamma ray dose FIA is a virtual constant for all device types analyzed here.
The relationships between marrow dose and FIA dose components as depicted in Figures IV-4 through IV-8 are tabulated in Table IV-2, as coefficients for the formula

\[
D_{\text{marrow}} = F_{\gamma} D_{\gamma,\text{FIA}} + (F_{n-n} + F_{n-\gamma}) D_{n,\text{FIA}}
\]

where

- \( D_{\text{marrow}} \) is reference man marrow dose, rad (marrow),
- \( D_{\gamma,\text{FIA}} \) and \( D_{n,\text{FIA}} \) are, respectively, free-in-air gamma ray and neutron doses, rad (tis),
- \( F_{\gamma} \) is the fraction of the free-in-air gamma ray dose converted to marrow dose, and
- \( F_{n-n} \) and \( F_{n-\gamma} \) are, respectively, the fractions of the free-in-air neutron dose converted into marrow neutron and gamma ray dose.

The values of these coefficients do not vary by more than a few percent over the range from 100 to 1000 rad (tis) FIA.

The relationships described above were derived for the purpose of relating average marrow dose to FIA dose, assuming isotropic incidence and infinite air spectra. Spectral variations will have little effect on the gamma ray marrow dose as it relates to the FIA dose, since the marrow dose deposition factors and the KERMA factors vary with energy in approximately the same manner over most of the energy range considered, and particularly at the higher energies which contribute the highest fraction of the gamma ray dose. On the other hand, the ratio of marrow response to tissue KERMA (FIA) for neutrons rises by a factor of 3 from group 24 (.052 to .111 MeV) to group 20 (1.1 to 1.8 MeV) and doubles again by group 4 (13.8 to 14.2 MeV). Therefore, accounting for the spectral hardening caused by the presence of the ground will increase the marrow neutron dose relative to the free-in-air neutron dose produced by the same fluence. In the case of the \( n-\gamma \)
marrow dose component the opposite effect takes place. This is caused by the decrease in number fluence required to produce the same FIA dose with the harder spectrum. A shift in effective neutron energy from 80 keV to 1.5 MeV decreases the fluence required to produce a given free-in-air dose by a factor of 5.5. Therefore, it is likely that, on the whole, spectral hardening due to the presence of the ground will result in a net decrease in marrow dose relative to a constant free-in-air dose.

The gamma ray marrow dose deposition in reference man is a very weak function of incident angle. Thus, even though the photon fluence is highly peaked in the direction away from the burst, the effect of this anisotropy is not likely to be very great. On the other hand, the neutron-induced gamma ray (n-\gamma) marrow dose component and the neutron (n-n) component show substantial angular dependence. This is especially true of the azimuthal angle of incidence in the midplane of the body, in which neutrons of all energies are approximately twice as effective at depositing dose in the marrow of reference man for a posterior incidence as they are for an anterior incidence. As noted earlier, neutrons above about 100 keV exhibit a strong directional bias away from the burst, which increases with neutron energy. As a result, for the case of a low air burst, the orientation of reference man, i.e., facing toward or facing away from the burst, will probably result in total marrow neutron dose extremes which are on the order of half or double the value for the isotropic case, respectively.

It does not take incident fluence anisotropy alone to produce nonuniform dose distribution in reference man, particularly from neutrons. Figures IV-9 through IV-11 show marrow dose distribution resulting from isotropically incident weapon radiation fluences produced by three very different weapons. Note that in all three cases the gamma ray (\gamma-\gamma) and neutron (n-n) dose to the submerged marrow in the pelvis, spine and legs is considerably less than that
deposited in the surface marrow, in the case of neutron dose by a factor of two or more. This is not the case for the neutron-induced gamma ray dose component. These gamma rays are produced throughout the mass of reference man with energies in excess of 2 MeV. Thus, their transport is little affected by the body and the amount of dose they deposit in any given region is determined mainly by geometrical considerations, i.e., the marrow location relative to that at which the gamma rays are being generated. The submerged marrow is surrounded by the torso and upper leg mass, which constitutes the majority of the reference man and is the region in which most of the gamma rays are produced. The rib cage surrounds most of this region. Therefore, it is expected that these marrow regions would receive the larger neutron-induced gamma ray dose, as indeed the case. It should be noted that these profiles, particularly those for neutrons, could look considerably different in the case of an anisotropic fluence which emphasized posterior exposure.
<table>
<thead>
<tr>
<th>Weapon Type</th>
<th>Yield (kt)</th>
<th>Height of Burst (m)</th>
<th>Height of Detector (m)</th>
<th>Air Density (mg/cc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Gun Assembly</td>
<td>5</td>
<td>104</td>
<td>1</td>
<td>1.13</td>
</tr>
<tr>
<td>2. Implosion, Fission</td>
<td>5</td>
<td>104</td>
<td>1</td>
<td>1.13</td>
</tr>
<tr>
<td>3. Implosion, Boosted Fission</td>
<td>5</td>
<td>104</td>
<td>1</td>
<td>1.13</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>61</td>
<td>1</td>
<td>1.13</td>
</tr>
<tr>
<td></td>
<td>.5</td>
<td>48</td>
<td>1</td>
<td>1.13</td>
</tr>
<tr>
<td>4. Enhanced Radiation</td>
<td>5</td>
<td>104</td>
<td>1</td>
<td>1.13</td>
</tr>
<tr>
<td>5. Little Boy (15) (Gun Assembly)</td>
<td>12.5</td>
<td>570</td>
<td>1</td>
<td>1.13</td>
</tr>
<tr>
<td>6. Fat Man (15) (Implosion)</td>
<td>22</td>
<td>500</td>
<td>1</td>
<td>1.13</td>
</tr>
</tbody>
</table>
Table IV-2

MARROW DOSE RAD MARROW (rad (marrow)) PER UNIT FREE-IN-AIR DOSE (rad (tis)) FOR SELECTED WEAPON TYPES

<table>
<thead>
<tr>
<th>Weapon Type</th>
<th>$F_{\gamma-\gamma}$ (FSD)</th>
<th>$F_{n-n}$ (FSD)</th>
<th>$F_{n-\gamma}$ (FSD)</th>
<th>$F_{n-n}+F_{n-\gamma}$ (FSD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Gun Assembly</td>
<td>.72 (.040)</td>
<td>.26 (.136)</td>
<td>.26 (.181)</td>
<td>.52 (.158)</td>
</tr>
<tr>
<td>2. Implosion, Fission</td>
<td>.72 (.040)</td>
<td>.26 (.134)</td>
<td>.26 (.181)</td>
<td>.52 (.158)</td>
</tr>
<tr>
<td>3. Implosion, Boosted Fission</td>
<td>.72 (.040)</td>
<td>.27 (.126)</td>
<td>.24 (.180)</td>
<td>.51 (.151)</td>
</tr>
<tr>
<td>5 kt</td>
<td>.72 (.040)</td>
<td>.27 (.126)</td>
<td>.24 (.180)</td>
<td>.51 (.151)</td>
</tr>
<tr>
<td>1 kt</td>
<td>.72 (.040)</td>
<td>.27 (.126)</td>
<td>.24 (.180)</td>
<td>.51 (.151)</td>
</tr>
<tr>
<td>.5 kt</td>
<td>.72 (.040)</td>
<td>.27 (.126)</td>
<td>.24 (.180)</td>
<td>.51 (.151)</td>
</tr>
<tr>
<td>4. Enhanced Radiation</td>
<td>.71 (.041)</td>
<td>.34 (.098)</td>
<td>.18 (.176)</td>
<td>.52 (.125)</td>
</tr>
<tr>
<td>5. Little Boy</td>
<td>.72 (.040)</td>
<td>.22 (.179)</td>
<td>.40 (.188)</td>
<td>.62 (.185)</td>
</tr>
<tr>
<td>6. Fat Man</td>
<td>.72 (.040)</td>
<td>.26 (.130)</td>
<td>.25 (.181)</td>
<td>.51 (.155)</td>
</tr>
</tbody>
</table>
Figure IV-1. Total Radiation Dose (rad (tis) free-in-air) versus Ground Range (meters) for Eight Selected Weapon Types.
Figure IV-2. Neutron Radiation Dose (rad (tis) free-in-air) versus Ground Range (meters) for Eight Selected Weapon Types.
Figure IV-4. Active Marrow Total Dose (rad (marrow)) versus Free-In-Air Total Dose (rad (tis)) for Eight Selected Weapon Types.
Figure IV-5. Active Marrow Neutron (n-n) Dose (rad (marrow)) versus Free-In-Air Total Dose (rad (tis)) for Eight Selected Weapon Types.
Figure IV-6. Active Marrow Neutron (n-n) Dose (rad (marrow)) versus Free-In-Air Neutron Dose (rad (tis)) for Eight Selected Weapon Types.
Figure IV-7. Active Marrow Neutron-Induced Gamma Ray (n-\(\gamma\)) Dose (rad (marrow)) versus Free-In-Air Neutron Dose (rad (tis)) for Eight Selected Weapon Types.
Figure IV-8. Active Marrow Gamma Ray Dose (rad (marrow)) versus Free-In-Air Gamma Ray Dose (rad (tis)) for Eight Selected Weapon Types.
Figure IV-9. Marrow Dose Distribution Per Unit Incident Isotropic Fluence from Little Boy (12.5 kt, Ground Range = 1.0 km), ○ : $F_{\gamma-\gamma}$, △ : $F_{n-n}$, □ : $F_{n-\gamma}$.
Figure IV-10. Marrow Dose Distribution Per Unit Incident Isotropic Fluence from a Boosted Fission Implosion Weapon (5 kt, Ground Range = 1.2 km), ○ : F_{\gamma-\gamma}, △ : F_{n-n}, □ : F_{n-\gamma}. 

Marrow Dose Per Unit Tissue Dose (F)

Marrow Fraction
Figure IV-11. Marrow Dose Distribution Per Unit Incident Isotropic Fluence from an Enhanced Radiation Weapon (5 kt, Ground Range = 1.5 km), ○ : F_{\gamma-\gamma}, △ : F_{n-n}, □ : F_{n-\gamma}.
SECTION V
SUMMARY AND CONCLUSIONS

Dose deposition in the active bone marrow was calculated for reference man \((11,12)\) using the MORSE Monte Carlo transport Code \((4,5)\) in the adjoint mode. Calculations were performed using cross sections from the 37 neutron-21 gamma ray group DNA Few Group Library \((6)\) with scattering angle dependence treated with a \(P_3\) Legendre expansion. KERMA factors used in the calculation of dose were those for active marrow alone for neutron dose and active marrow plus trabecular bone for photon dose. The distinction was made to properly maintain the condition of local charged particle equilibrium required for KERMA use. Adjoint transport calculations resulted in dose deposition \((\text{rad (marrow)})\) values for eight marrow regions as a function of energy and angle differential neutron and gamma ray fluences externally incident on the man phantom. These regions and the relative amount of marrow in each are:

<table>
<thead>
<tr>
<th>Region</th>
<th>Total Active Marrow Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Pelvis</td>
<td>0.362</td>
</tr>
<tr>
<td>2. Vertebrae (spine)</td>
<td>0.284</td>
</tr>
<tr>
<td>3. Skull</td>
<td>0.131</td>
</tr>
<tr>
<td>4. Ribs and sternum</td>
<td>0.102</td>
</tr>
<tr>
<td>5. Scapulae</td>
<td>0.048</td>
</tr>
<tr>
<td>6. Legs</td>
<td>0.038</td>
</tr>
<tr>
<td>7. Arms</td>
<td>0.019</td>
</tr>
<tr>
<td>8. Clavicles</td>
<td>0.016</td>
</tr>
</tbody>
</table>

Dose deposition (or response) functions for these regions were recorded for gamma dose from incident gamma rays \((\gamma-\gamma)\) gamma dose from incident neutrons \((n-\gamma)\) and neutron dose from incident neutrons \((n-n)\). These were recorded in the energy group structure mentioned previously in angle-integrated and angle-differential form, the latter
being recorded in twelve equal solid angle increments. These values
may be folded with any desired incident radiation fluence to obtain
dose to the active marrow. The only condition for their direct use
is that the man be situated in a radiation fluence which is uniform
across his extremities. Man standing on an open plane meets this
condition, man in a vehicle, in a foxhole or lying on the ground
does not.

Calculated γ-γ and n-n response values show strong dependencies
on the energy of the incident radiation. For γ-γ deposition this
dependency closely follows that of gamma ray tissue KERMA. For n-n
deposition, strong shielding of the marrow from high energy neutrons
by the highly hydrogenous body mass results in a response value
which decreases much more rapidly than neutron tissue KERMA down
to energies of a few hundreds of keV. Below this energy the n-n
deposition per unit fluence is independent of neutron energy. The
reason for this is that neutrons in this energy range thermalize
rapidly within the body and remain there to deposit the greatest
part of their n-n component by thermal capture in nitrogen, which
yields a 626 keV proton. The calculated n-γ response values show
virtually no dependence on incident neutron energy. Instead they
depend almost solely on the total incident neutron number fluence.
As such they form a floor, below which the total neutron response
cannot sink.

Calculated γ-γ response values show little dependence on angle
of incidence with the man phantom. However, neutrons incident on
the posterior in the midplane of the phantom are approximately
twice as effective as depositing marrow dose as would be isotrop-
ically incident neutrons of the same energy.

Dose to the marrow has been calculated for radiation fluences
from several hypothetical and real weapon types. These fluences
reflect spectral characteristics of transport through homogeneous
air and have been assumed to be isotropic. Results indicate that
all those weapon types considered are equal in the efficiency with which their associated free-in-air gamma ray dose environments deposit dose in the marrow (~72%). With the exception of the Little Boy weapon, all are also nearly equal in the efficiency with which their associated free-in-air neutron dose environments deposit an average total dose in the marrow (~52%). However, the neutron environment from the enhanced radiation weapon deposits two-thirds of this average by direct neutron interaction (kinetic energy transfer and charged particle emission), while the more conventional nuclear devices deposit only about half the average in this manner. The Little Boy weapon is a special case, possessing an exceptionally large transported low energy neutron component and having an average total marrow dose/free-in-air tissue dose conversion efficiency of 62%. Of this total only about a third is deposited by direct neutron interaction; the remainder are deposited by neutron-induced gamma rays.

The marrow dose calculations described above also indicate that the dose components are not uniformly distributed, even for the case of isotropic incidence. This is particularly true of the direct interaction neutron component. Neutron environments for all weapon types considered deposited at least twice the direct interaction dose in the 32% shallow marrow (skull, ribs, scapulae, arms, clavicles) as in the 68% deep marrow (pelvis, spine, legs). Weapon gamma ray environments display a similar bias, but to a much lesser extent, about 1.15 to 1. On the other hand, neutron-induced gamma rays deposit their dose preferentially in the deep marrow, which is central to the region in which they are produced, and in the ribs, which surround a large portion of that region. The extent to which this is the case is sufficient to produce an almost uniform gamma ray dose over the marrow in reference man exposed to weapons radiation having a neutron to gamma ray dose ratio of unity.
RADIATION DOSE DEPOSITION IN THE ACTIVE MARROW OF REFERENCE MAN--ETC(U)

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These calculations have been performed with the best available man model, code and cross sections. The man model is a free-world standard. The code and cross sections have been extensively tested against experiment and previously calculated data (22). The overall fractional standard deviation (FSD) of the total marrow doses calculated for the example weapon types are less than 0.11. The resulting confidence in the results reported herein must leave the reader with a dilemma, however. This dilemma concerns the choice of an exposure criterion for use by the military to adequately assess the risks of its field personnel and collaterally exposed civilians to mortality from the early marrow syndrome. According to Figure I-1, taken from the Reactor Safety Study report (1) and reproduced in the introduction of this report, the average marrow dose required to produce LD<sub>50</sub> (50% mortality in man, death in 30-60 days) is 340 rads (marrow). This value has been obtained from cases of human exposure to photon radiation. Application of the average marrow dose/free-in-air conversion factors for the initial gamma radiation fields produced by typical modern weapons, as shown in Table IV-2, results in a required exposure of 472 rad (tis) free-in-air to produce the 340 rad (marrow) dose. The uncertainties in the marrow dose criterion and transport combined are approximately 11%, therefore within these limits of uncertainty the LD<sub>50</sub> exposure criterion calculated for weapon gamma rays is in good agreement with the equivalent value most commonly cited in DoD reports (23), which is 450 rad (tis) FIA. Thus, for troops at the periphery of an initial radiation field produced by a weapon larger than about 100 kt, the current DoD criterion appears to be quite adequate.

The dilemma arises when a choice of an early mortality criterion must be made for the case of exposure to the mixed neutron-gamma radiation field typical of a low yield nuclear weapon. The level of exposure to weapon neutrons alone which is required to produce an LD<sub>50</sub> marrow dose becomes 580 to 610 rad (tis) FIA, depending on weapon type and yield. Of course, these large exposure
requirements are valid only if it is true that the average marrow
dose parameter is a valid number of merit in relation to such an
effect and that the relative biological effectiveness (RBE) of
neutron dose for this effect is unity, i.e., that neutrons and
gamma rays are equally effective at producing the phenomena which
in turn produce early mortality.

The extent to which the average marrow dose is a valid number
of merit for the prediction of the effect of interest depends on the
amount of dose nonuniformity already allowed for in obtaining the
criterion value. Since this value was obtained for the case of pure
gamma ray exposure this amount is quite small, with the minimum
marrow dose probably being within 6% of the average. In the event
of exposure to a mixed neutron-gamma ray field it is possible for
the minimum marrow dose to be much less than 90% of the average
value. In this case the average marrow dose is probably not a
valid number of merit for the prediction of mortality from the
acute marrow syndrome. A better number would be the minimum dose,
since it applies to so much of the marrow. This conclusion is
supported by the findings of Bond and Robinson (2) which are summar-
ized as follows:

1. Survival in most mammals exposed to amounts of penetrat-
ing radiation in the hematological syndrome range depends
primarily on maintenance of a critical level of neutro-
phils and platelets in the peripheral blood.

2. This minimum level depends on the survival (or prolifera-
tive integrity) of a critical number or fraction of
the stem cells in the total marrow mass, regardless of
distribution of surviving cells in that mass.

3. Each species of mammal has its own criterion for survival
probability as a function of surviving stem cell number
or fraction.

Using the minimum marrow dose as the number of merit in acute marrow
syndrome mortality prediction changes the LD$_{50}$ gamma ray exposure
criterion very little; however, it increases that for the mixed
radiation fields of the modern weapons considered to between 650 and 700 rad (tis) FIA, depending on weapon type and size.

All exposure values for mixed radiation fields cited above were produced under the assumption of a neutron dose RBE of unity. However, most available evidence suggests that the neutron dose RBE for the acute marrow syndrome is greater than 1. Bond and Robinson (2) obtained a value of 1.4 in their canine experiments, though they admit that this is a rough estimate. Katz et al., have obtained information which suggests that the RBE for stem cell proliferative integrity, albeit in mice, lies in the range of 3 to 4. This range is applicable for neutron doses in excess of 100 rad (marrow) and neutron energies between .5 and 2 MeV. According to Katz, RBE values increase exponentially with decreasing marrow dose. On the basis of these pieces of evidence it seems reasonable to assume that, for the effect of interest, likely upper and lower bounds of the RBE value are 3.5 and 1.4, respectively. If this is indeed the case, then on the basis of average marrow dose the ranges of exposures necessary to produce 340 REM (marrow) are 300 to 330 rad (tis) FIA for the upper bound RBE value and 500 to 530 for the lower bound, depending on weapon type. On the basis of minimum marrow dose, as discussed previously, these dose ranges would be 360 to 410 for the upper bound RBE value and 575 to 625 for the lower bound. Again, applicable values within each range depend on weapon type and size. Lower dose values apply to enhanced radiation devices, while higher dose values apply to other weapon types and increase with weapon size.

It would seem that, on the basis of data reported herein and interpreted in the above discussion, one faces a considerable dilemma in choosing the correct mortality probability criterion for the case of exposure to a mixed neutron-gamma radiation field. According to present knowledge of the RBE for neutrons pertaining to the early
mortality effect, the criterion for LD₅₀ equivalent exposure is most likely to be between 330 and 625 rad (tis) FIA for non-radiation enhanced tactical weapons and between 300 and 575 rad (tis) FIA for enhanced devices. Lesser lower bounds than those given above are conceivable, while it is unlikely that the criterion would approach, much less exceed, the given upper bound.

Research on radiation effects at the cellular level has progressed to the point at which it is possible to predict the probability of many such effects, including proliferative integrity, resulting from exposure to any incident radiation field, high LET, low LET or a mixture thereof. This is providing that the dose levels of interest are on the order of a rad or more. The adjoint Monte Carlo approach demonstrated here for the calculation of gross energy deposition in human marrow from incident neutron and gamma radiation may also be used to calculate the probability of such cellular effects in situ, providing the appropriate cellular response parameters are substituted for KERMA. The results of such a calculation for the probability of marrow cell proliferative integrity could be made relevant to the prediction of acute marrow syndrome mortality probability by calibration to available criteria based on pure photon exposure. Such a procedure would remove the need to consider appropriate dose values of merit or the RBE if high LET radiation, since all such consideration would be implicit in the cellular effect calculation. With these results in hand it would be possible to determine mortality probability criteria for whole body exposure to radiation of all weapon types as well as for scenarios which involve nonuniform shielding of the body, such as troops in foxholes, tank crews, etc. However, until such time as the cellular-effect based calculations are performed and appropriate acute marrow syndrome mortality probability criteria are established for mixed-LET radiation exposures, the nominal exposure criterion of 450 rad (tis) FIA for LD₅₀ equivalence should be used with extreme caution.
For exposure to radiation fields from typical tactical nuclear weapons
the 450 rad value is encompassed by an uncertainty range so large
(± 33%) as to preclude its selection as the actual criterion from
being other than fortuitous.
SECTION VI
REFERENCES


REFERENCES (Cont'd)


22. Scott, W.H., Jr., et. al., In-Missile Calculations of Silicon Dose-A Comparison with Experiment, DNA 3830F, September 1975.

APPENDIX A
MATHEMATICAL DESCRIPTION OF THE REFERENCE MAN PHANTOM

The mathematical description of the external configuration of the reference man phantom and that of its internal organs is based on that published in, "A Tabulation of Dose Equivalent per Microcurie-Day for Source and Target Organs of an Adult for Various Radionuclides," ORNL-5000, W.S. Snyder, et. al., November 1974. The conversion of the Snyder descriptive equations into the combinatorial geometry format required by the MORSE Monte Carlo transport code required only a single modification. The Snyder phantom contains head, skull and lungs which are described in total or in part by ellipsoids. However, combinatorial geometry is limited to the description of prolate or oblate spheroids. Therefore, the ellipsoid-spheroid conversion was made when necessary, conserving volume and approximating the original configuration as closely as possible.

Exterior of the Phantom

The body is represented as erect with the positive z-axis directed upward toward the head. The x-axis is directed to the phantom's right and the y-axis is directed toward the anterior side of the phantom. The origin is taken at the center of the base of the "trunk" section of the phantom. The axes are calibrated in centimeters.

The "trunk" is a solid elliptical cylinder specified by

$$\left( \frac{x}{20} \right)^2 + \left( \frac{y}{10} \right)^2 \leq 1, \quad 0 \leq z \leq 70$$
so that the "trunk" includes the arms as well as the pelvic and hip bones from the point where the separation of the legs begins. The volume of the trunk section is 43,982 cm³, and the mass, as indicated below, is 42,701 g.

The head section is a right elliptical cylinder topped by half a prolate spheroid. The locus is specified by

\[
\left( \frac{x}{7} \right)^2 + \left( \frac{y}{10} \right)^2 \leq 1, \quad 70 \leq z \leq 85.5
\]

or

\[
\left( \frac{x}{7.713} \right)^2 + \left( \frac{y}{10} \right)^2 + \left( \frac{z-85.5}{7.713} \right)^2 \leq 1, \quad 85.5 \leq z \leq 93.213
\]

The total volume is 4,655 cm³, and the mass, as indicated below, is 5,083 g.

The leg region of the phantom consists of the frustums of two circular cones specified by

\[
x^2 + y^2 \leq x \left( 20 + \frac{z}{5} \right), \quad -80 \leq z \leq 0,
\]

where the plus sign defines the right leg and the minus sign the left. The total volume of both legs is 20,776 cm³, and the mass, as discussed below, is 21,901 g. It is apparent that the leg region does not join smoothly to the trunk region, because the legs protrude slightly beyond the ellipse defining the trunk in the plane z = 0.

The genitalia region (male) of the phantom consists of the region specified by

\[-4.8 \leq z \leq 0 - \left( 10 + \frac{z}{10} \right) \leq x \leq 10 + \frac{z}{10}, \quad \left( 10 + \frac{z}{10} \right) \geq y \geq 0,\]

and

\[
\left( x \pm \left( 10 + \frac{z}{10} \right) \right)^2 + y^2 \leq \left( 10 + \frac{z}{10} \right)^2,
\]

and this last inequality must hold for either choice of sign, i.e., the
genitalia region lies outside both legs. The genitalia region has a volume of 196.3 cm$^3$ and a mass of 193.7 g.

Organs

Skeletal System. The skeletal system consists of the 8 parts described below. A view of the total skeleton is shown in Figure A-1.

Leg Bones. Each leg bone is the frustum of an elliptical cone. The expression for the right leg bone is

$$\left(x - 10 - \frac{8}{79.8} z\right)^2 + y^2 \leq \left(3.5 + \frac{2.5}{79.8} z\right)^2, \quad 79.8 \leq z \leq 0.$$  

The volume of both bones is 2,799 cm$^3$, and the mass is 4,160 g.

Arm Bones. Each arm bone is the frustum of an elliptical cone. The right one is defined by

$$\left[\frac{1.4}{138} (z-69) + (x-18.4)\right]^2 \leq \frac{138 + (z-69)}{138}, \quad 0 \leq z \leq 69.$$  

The volume of both arm bones is 956 cm$^3$ and the mass is 1,421 g.

Pelvis. The pelvis is a portion of the volume between two nonconcentric circular cylinders described by

$$x^2 + (y - 3)^2 \leq (12)^2$$
$$x^2 + (y - 3.8)^2 \leq (11.3)^2$$
$$y - 3 \leq 0$$
$$0 \leq z \leq 22$$
$$y \geq -5 \text{ if } z \leq 14.$$  

Its volume is 606.1 cm$^3$ and its mass is 900.8 g.

Spine. The spine is an elliptical cylinder given by

$$\left(\frac{x}{2}\right)^2 + \left(\frac{y + 5.5}{2.5}\right)^2 \leq 1, \quad 22 \leq z \leq 78.5,$$
and has a volume of 887.5 cm$^3$ and a mass of 1,319 g.

Skull. The skull is the volume between two nonconcentric defined by

\[
\left(\frac{x}{6.245}\right)^2 + \left(\frac{y}{9}\right)^2 + \left(\frac{z-86.5}{6.245}\right)^2 \geq 1
\]

\[
\left(\frac{x}{7.513}\right)^2 + \left(\frac{y}{9.8}\right)^2 + \left(\frac{z-85.5}{7.513}\right)^2 \leq 1
\]

and has a volume of 846.8 cm$^3$ and a mass of 1,258 g.

Rib Cage. The rib volume is a series of bands between two concentric, right-vertical, elliptical cylinders. This region is sliced by a series of equispaced horizontal planes into slabs, every other slice being a rib. The statements that must be satisfied are

\[
\left(\frac{x}{17}\right)^2 + \left(\frac{y}{9.8}\right)^2 \leq 1
\]

\[
\left(\frac{x}{16.5}\right)^2 + \left(\frac{y}{9.3}\right)^2 \geq 1
\]

\[
35.1 \leq z \leq 67.3;
\]

Integer \( z-35.1 \) is even

Integer \( u \) is the integral part of \( u \), i.e., integer \( (3.67) = 3 \), etc. Thus, "integer \( z-35.1 \) is even" amounts to requiring that

\[
0 \leq \frac{z-35.1}{1.4} < 1 \text{ or } 2 \leq \frac{z-35.1}{1.4} < 3 \text{ or } 4 \leq \frac{z-35.1}{1.4} < 5, \text{ etc.}
\]

The total rib volume is 694 cm$^3$ and the mass is 1,031 g.

Clavicles. The clavicles are represented as two portions of an annular region between two concentric right-vertical elliptical cylinders. The statements which must be satisfied are

\[
\left(\frac{x}{20.7}\right)^2 + \left(\frac{y+11.1}{20.7}\right)^2 \leq 1
\]
\[ \left(\frac{x}{19.3}\right)^2 + \left(\frac{y-11.1}{19.3}\right)^2 \geq 1 \]

\[ 10 > |x| > 1.4076 \]

\[ y > 0 \]

\[ 68.95 \geq z \geq 67.55 \]

The volume of both clavicles is approximately 54.7 cm\(^3\), and the mass is approximately 82 g.

Scapulae. The scapulae extend from \(z = 5.09\) to \(z = 67.3\). The latter value corresponds to the top of the rib cage rather than the top of the 12th rib \((z = 64.5 \text{ cm})\) as in the Snyder prescription. This variation was inadvertent but should have no material effect on the calculational results. The scapulae lie between two elliptical cylinders.

\[ \left(\frac{x}{17}\right)^2 + \left(\frac{y-5.8}{9.8}\right)^2 = 1 \text{ (outer surface of ribs)} \]

and

\[ \left(\frac{x}{19}\right)^2 + \left(\frac{y}{9.8}\right)^2 = 1 \text{ (a somewhat larger cylinder)}. \]

Although the lower portion of the scapula is somewhat smaller than the upper, this distinction is ignored here, as in the Snyder model. Thus, the scapulae occupy all the above space between the planes

\[ |x| \geq 10.2956 \]

\[ y \leq -4.2744 \]
In Fig. A-1, a human adult skeleton has been sketched, and the areas which contain active bone marrow (red bone marrow) are cross-hatched. The idealized skeleton used for the phantom is sketched also with the corresponding areas cross-hatched. The red, or active, bone marrow is taken to total 1,500 g, and the same weight is assigned to yellow bone marrow. The weights of the two marrow types are given in Table A-1, and they are assigned to the corresponding regions of bone and are assumed to be uniformly distributed in these regions.

**Lungs.** Each lung is half a prolate spheroid with an anterior section removed. The defining expressions for the left lung are

\[
\left( \frac{x - 8.5}{6.25} \right) + \left( \frac{y}{6.25} \right) + \left( \frac{z - 43.5}{24} \right) \leq 1,
\]

\[z \geq 43.5,\]

\[
\left( \frac{x - 1.8769}{6.25} \right) + \left( \frac{y}{6.25} \right) + \left( \frac{z - 43.5}{24} \right) \geq 1 \text{ if } y > 0.
\]

The volume of both lungs is 3,378 cm$^3$ and the mass is 999.2 g.
Table A-1  Masses of Red and Yellow Marrow and Bone in the Phantom

<table>
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<tr>
<th>Bone Region</th>
<th>Red Marrow (g)</th>
<th>Bone (g)</th>
<th>Yellow Marrow (g)</th>
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<td>Legs</td>
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<tr>
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<tr>
<td>Pelvis</td>
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<td>181</td>
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<tr>
<td>Ribs</td>
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<tr>
<td>Cranium***</td>
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<td>557</td>
<td>59.5</td>
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<tr>
<td>Mandible†</td>
<td>18</td>
<td>439</td>
<td>6</td>
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<tr>
<td>Spine</td>
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<td>TOTAL</td>
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<td>7474</td>
<td>1500</td>
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</table>

*69 \geq z \geq 52.6  \quad **0 \geq z \geq -22.8  \quad ***z \geq 3y + 77

†y \geq 0, 77.99 \leq z \leq 80.26
Fig. A-1. Idealized model of the skeleton for computer calculations (left) and a more realistic representation (right) with percentages of red bone marrow found in the shaded portions of the bones. Clavicles and scapulae not shown in phantom.
APPENDIX B
ANGLE-INTEGRATED DOSE DEPOSITION FACTORS

This appendix contains tabulated active marrow dose deposition factors for $4\pi$ angle-integrated incident fluence in 37 neutron and 21 gamma ray energy groups. Table II-2, which gives the energy boundaries for these groups, is reproduced here for the reader's convenience. Tabulated dose deposition factors are presented for eight skeletal regions and for reference man. The reference man values have been obtained by weighting the skeletal region responses by their respective marrow fractions and taking the sum for all eight regions. Tabulated quantities include neutron (n-n), gamma ray (n-$\gamma$) and total (n-t) dose deposition per unit incident neutron fluence and gamma ray dose ($\gamma$-$\gamma$) per unit incident gamma ray fluence. Note that use of the dose deposition factors contained in this appendix implies the assumption of isotropic incident fluence.
Table II-2 NEUTRON AND GAMMA-RAY ENERGY BOUNDARIES
FOR THE 37-21 COUPLED NEUTRON-GAMMA LIBRARY

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<th>Gamma Group (eV)</th>
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*Read as 1.96x10^7.
### ANGLE-INTEGRATED DOSE DEPOSITION FACTORS

Neutron Dose Deposition From Incident Neutron Fluence

(rad (marrow) per unit fluence per energy group)

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* REGION

** REGION ACTIVE MARROW FRACTION
ANGL-E-INTEGRATED DOSE DEPOSITION FACTORS

Gamma Ray Dose Deposition From Incident Neutron Fluence
(rad (marrow) per unit fluence per energy group)

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* REGION

** REGION ACTIVE MARROW FRACTION

123
### ANGLE-INTEGRATED DOSE DEPOSITION FACTORS

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(rad (marrow) per unit fluence per energy group)

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* REGION

** REGION ACTIVE MARROW FRACTION
APPENDIX C
ANGLE-DIFFERENTIAL DOSE DEPOSITION FACTORS

This appendix contains tabulated active marrow dose deposition factors for incident fluence in 12 equal solid angle bins (1.047 steradians per bin) arranged in 5 polar angle bands. Figure III-16 from the report text gives the orientation of these angle bins relative to the reference man phantom and is reproduced here for the readers convenience. Also reproduced is Table II-2, which gives the boundaries for the neutron and gamma ray energy group structure. Tabulated dose deposition factors are presented for eight skeletal regions and for reference man. The reference man values have been obtained by weighting the skeletal region responses by their respective marrow fractions and taking the sum for all eight regions. Tabulated quantities include neutron (n-n), gamma ray (n-γ) and total (n-t) dose deposition per unit incident neutron fluence per angle bin and gamma ray dose (γ-γ) per unit incident gamma ray fluence per angle bin. NOTE: These angle differential values are for marrow on the right (positive X) side of the phantom only. To obtain azimuthal angle differential results for marrow located on the left (negative X) side of the phantom the recorded azimuthal responses must be transposed across the Y-Z plane. The dose deposition for the total marrow (left and right) of a body region or of reference man as a whole in a particular azimuthal angle bin is the average of the tabulated and transposed value for that bin. In such case, dose deposition in three pairs of angle bins, 2 and 3, 5 and 7, and 9 and 10, would be the respective average of each.
This appendix also contains tabulated data for active marrow dose deposition in reference man for incident fluence in 5 polar angle bands. These values have been obtained by averaging the azimuthal bin values in each polar band. The results are tabulated for neutron (n-n), gamma ray (n-γ) and total (n-t) dose deposition per unit incident neutron fluence per angle bin and gamma ray dose (γ-γ) per unit incident gamma ray fluence per bin. These data can be useful in situations where the population subject to analysis is erect but facing in random directions.
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*Read as 1.96x10^7.
Figure III-16 Solid Angle Bin Orientation for Adjoint Fluence Exit
(1.0472 steradians per bin)

Polar Orientation

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Azimuthal Orientation

Front (Anterior) +X

Back (Posterior) +Y

Azimuthal Bins and Cosine Boundaries

A 1
B 0.0
C 0.0
D 0.0
E 12

-0.87
-0.7
0.7
0.7
0.87
0.87
0.7
0.7
0.87
-0.87
AZIMUTHAL AND POLAR ANGLE-DIFFERENTIAL DOSE DEPOSITION FACTORS

Neutron Dose Deposition From Incident Neutron Fluence (n-n)

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AZIMUTHAL AND POLAR ANGLE-DIFFERENTIAL DOSE
DEPOSITION FACTORS

Gamma Ray Dose Deposition From Incident Neutron Fluence (n-γ)

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238
### AZIMUTHAL AND POLAR ANGLE-DIFFERENTIAL DOSE DEPOSITION FACTORS

Gamma Ray Dose Deposition From Incident Gamma Ray Fluence ($\gamma-\gamma$)

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*rad (marrow) per unit fluence per energy group per angle bin

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FACTORS FOR REFERENCE MAN

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## Polar Angle-Differential Dose Deposition Factors for Reference Man

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POLAR ANGLE-DIFFERENTIAL DOSE DEPOSITION FACTORS FOR REFERENCE MAN

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Science Applications, Inc.
ATTN: D. Kaul
ATTN: R. Jarka

ATTN: K. Pyatt