# RECONSTRUCTION OF EXTERNAL DOSE FROM BETA RADIATION SOURCES OF NUCLEAR WEAPON ORIGIN

Neil M. Barss and Ronald L. Weitz*

*Abstract*—**In response to requests from the Department of Veterans Affairs, a methodology was developed to assess the external dose accrued by personnel in the vicinity of beta radiation sources of nuclear weapon origin. This methodology has been applied in support of the Nuclear Test Personnel Review (NTPR) Program implemented by the Department of Defense. As required by the Code of Federal Regulations (Title 32, Part 218 and Title 38, Part 3.311), the NTPR Program must evaluate radiological hazards from nuclear testing activities that include alpha particle, beta particle, neutron, and photon emissions from radionuclides. Prior to the development of this methodology, only photon and neutron radiations were explicitly quantified for external dose assessments in this program. Alpha radiation of external origin presents no risk for biological effects due to external dose potential to skin tissue because of the particle's very limited range. However, beta particles are sufficiently penetrating to have such potential. Methods are provided to quantify ionizing radiation doses to the skin and lens of the eye from beta radiation sources of nuclear weapon origin located external to the body. This formulation allows the estimation of beta dose from a film badge (gamma) dose or from an equivalent reconstructed gamma dose.**
**Health Phys. 91(4):379–389; 2006**

**Key words: operational topic; atmospheric testing; atomic bomb; beta particles**

## INTRODUCTION

Personnel who participated in nuclear weapons testing accrued external beta doses to the skin and lens of the eye concurrently with gamma dose when exposed to regions of radioactive fallout or neutron-activated soil. While the gamma doses were often measured at the test sites with individual film badge dosimeters, these dosimeters did not reliably record the beta dose (NRC 1989). Therefore, analytical techniques must be employed to estimate the beta doses received by the test participants. This paper describes the methodology developed in the Nuclear Test Personnel Review (NTPR) Program for beta dose reconstruction. It is convenient, when quantifying the beta dose, to normalize it to the corresponding gamma dose as measured on a properly worn film badge. The resulting ratio of beta dose to gamma dose depends on the spectrum of the emitted radiation and on the geometric relationship between an individual and the source (e.g., distance from or height above the source). Because the beta and gamma energy spectra of weapon debris change significantly with time, the beta-to-gamma dose ratios can exhibit strong time dependencies. Due to the beta particle range and attenuation characteristics, true beta doses received are critically dependent on distance, geometry, and shielding material between the radioactive source and an individual. As a consequence, the nature of specific job- or task-related activities and their associated protective measures must be considered when reconstructing skin and eye doses.

In the development of this methodology, radiation transport computer programs and techniques were used to derive beta-to-gamma dose ratios for sources, times, and geometries relevant to the exposures incurred by nuclear weapon test participants. Fallout deposited on a surface is approximated as an infinite plane with uniform, isotropic emission from each point source in the plane. Acute and chronic beta doses are evaluated neglecting (1) self-attenuation of large fallout particles with volume-distributed radioactivity, (2) scattering and attenuation of emitted radiation due to surface roughness, and (3) radioactive source depletion over time due to weathering, chemical dissociation, environmental transport such as migration into the soil, and other dispersive mechanisms. While these simplifying approximations were made primarily to facilitate the calculations, they also ensure that the resultant beta dose predictions were not underestimated.

Site-specific skin doses, which include both beta and gamma dose components, are evaluated for the basal cell layer of the skin as the tissue at stochastic risk for cancer induction and at the anatomical location where a skin cancer has been medically diagnosed. Because the basal cells comprise the layer of skin between the epidermis and dermis and range in depth from 20 to 100 $\mu$m below

* SAIC, 8301 Greensboro Drive, Suite 510, McLean, VA 22102.
For correspondence contact N. Barss at above address, or email at neil.m.barss@saic.com.
(*Manuscript accepted* 2 *March* 2006)
0017-9078/06/0

the skin's surface, a 70-$\mu$m average depth is used for skin dose assessments (ICRU 1997). At this tissue depth, there is no dose from alpha particles emitted external to the body. A beta particle energy greater than $1.12 \times 10^{-14}$ J (0.07 MeV) is required to penetrate the dead epidermis skin layer; hence, beta particles with energies less than this threshold do not contribute to the skin dose. Doses to the lens of the eye are assessed at a depth of 3 mm below the anterior surface of the eye, where the tissue at risk for posterior subcapsular cataract development is located (ICRU 1997).

## METHODS

### Radiation source spectra

Nuclear weapon test participants were potentially exposed to prompt gamma and neutron emissions from the nuclear detonation, mixed fission products and actinides in fallout, and neutron activation products in the soil. The prompt gamma and neutron radiations themselves contributed to the skin and eye doses but posed no beta hazard. The remaining sources, however, contained beta-emitting isotopes and are specifically considered in the present formulation. The primary source of exposure for most test participants was the mixture of radioactive products that resulted from the fissioning of a nuclear device. These mixed fission products were most often deposited in the form of fallout, although other types of exposure also occurred (e.g., to aircraft contaminated by flying through the debris cloud).

ORIGEN is a well-known and widely used computer code for calculating the buildup and decay of radioisotopes from fission events (ORNL 1977). Finn et al. (1979) utilized this code, together with the ENDF/B-IV database (England and Stamatelatos 1976), to compute the gamma and beta energy spectra from fission product inventories at various times (from 0.5 h to 70 y) after the fissioning of $^{235}$U and $^{238}$U by fast neutrons and of $^{235}$U by thermal neutrons. Finn's spectra for fast neutron fissioning of $^{235}$U were used in this analysis to characterize the gamma and beta emissions from fission products produced in nuclear weapon detonations.

Sample beta spectra from the Finn compilation are displayed in Fig. 1. It is observed that both the intensity and shape of these spectra change significantly with time. The integrated intensity of the beta emissions decreases from about $1 \times 10^{-4}$ betas s$^{-1}$ per fission at 1 h to $3 \times 10^{-6}$ at 1 d and $3 \times 10^{-7}$ at 1 wk, while the curve shapes indicate a progressive "softening" of the energy spectra during this period. The spectral shape is important because the range of beta particles in air is a strong function of their energy. These spectral shifts can be characterized by the changes in the average energy of the emitted particles with time, as plotted in Fig. 2 for both beta and gamma emissions. On average, the beta emissions at early times (i.e., hours after the detonation) are much more energetic, and hence more penetrating, than those emitted days or weeks later. In contrast, the spectral

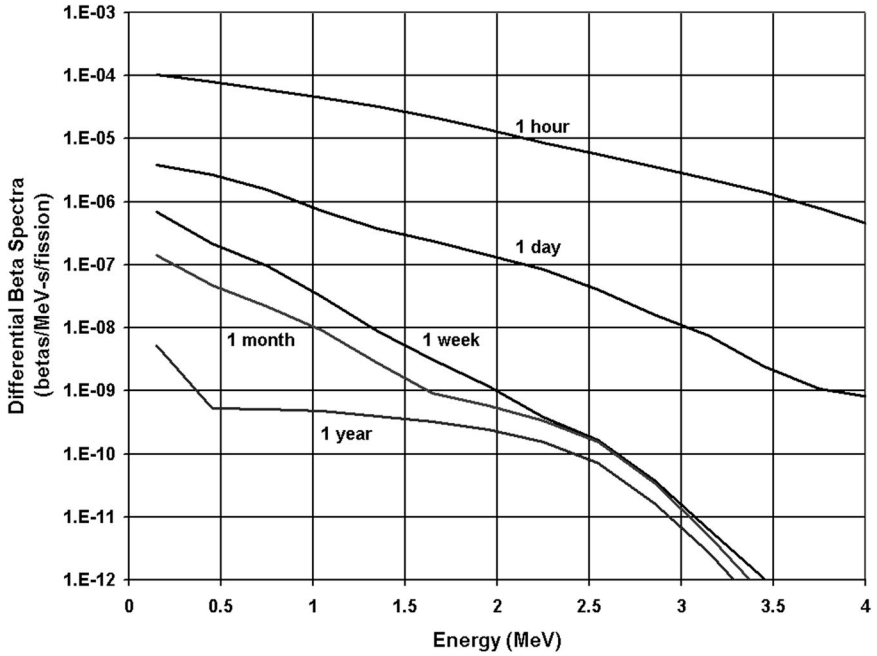


**Fig. 1.** Differential beta spectra at various times after a nuclear detonation (based on Finn et al. 1979).

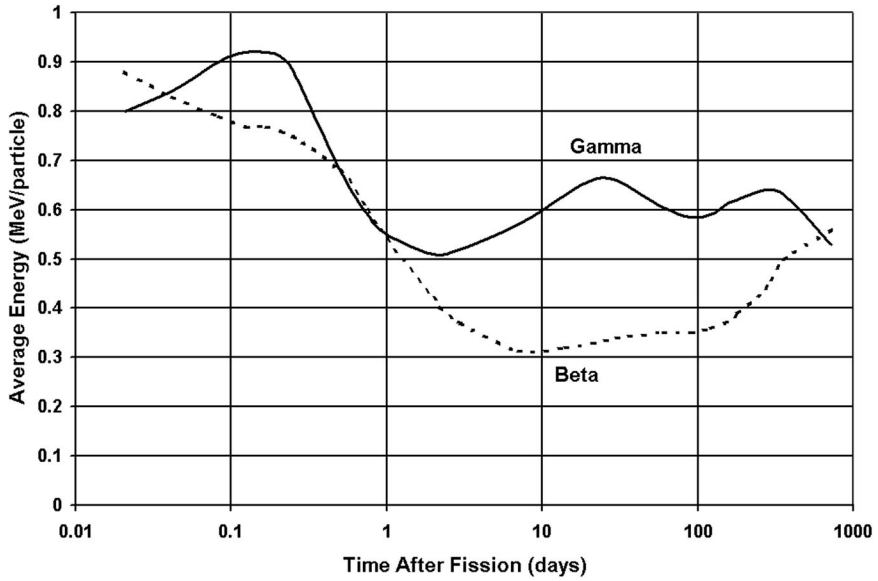


**Fig. 2.** Average energies of gamma and beta emissions as a function of time after a nuclear detonation (from Finn et al. 1979).

changes of gamma emissions are of little relative consequence because the mean free paths of gamma photons are much greater than the ranges of beta particles with comparable energies.

In addition to fission products, the debris from nuclear detonations inevitably contained unburned fissile materials (e.g., $^{235}$U and $^{239}$Pu) and their neutron reaction and decay products, collectively called actinides. The presence of these actinides constitutes an additional source of beta and gamma radiation not included in the Finn spectra. The significance of the actinide content has been evaluated by considering fallout from a large Pacific shot. The ORIGEN code was augmented with shot-specific radiochemistry data to calculate the actinide activity in unfractionated fallout as a function of time after detonation. Examination of the results reveals that only a few of these radionuclides were important contributors to the fallout radiation field during typical times of interest (hours to years after the detonation): $^{237}$U, $^{240}$U, $^{239}$Np, and $^{240m}$Np (isomeric state of $^{240}$Np). The gamma intensities for these isotopes were taken from the Evaluated Nuclear Data Files (ENDF) (LANL 2001), while their beta emissions were quantified with the subroutine BSPEC, part of the DOSFACTER computer code (U.S. DOE 1988). In both cases, the additional contributions of the actinides to the radiation field were numerically partitioned according to the Finn energy binning structure and added to the Finn spectra.

Activation products were produced in the soil beneath many detonations (typically those with heights of burst of 300 to 600 m) at the Nevada Test Site (NTS) by neutron absorption in resident materials. Test participants at NTS occasionally conducted maneuvers or visited displays in areas affected by neutron activation. In contrast, regions of activated soil or coral from the Pacific shots were rarely encountered by test participants, the vast majority of whom were not allowed near the shot sites. Through an evaluation of the isotopic abundances and absorption cross sections of typical soil constituents and the half lives of the radioactive products, the radioisotopes $^{24}$Na, $^{56}$Mn, $^{31}$Si, $^{45}$Ca, and $^{42}$K were identified as the primary contributors to the gamma and beta environments in the vicinity of activated soil for the first few weeks after detonation, and $^{46}$Sc and $^{60}$Co at later times (e.g., months to years after the detonation). Aluminum activation products decayed to immeasurable levels within minutes after a detonation and, therefore, did not contribute by the time test participants approached ground zero. These observations are consistent with field measurements made at nuclear detonation sites (e.g., Hashizume et al. 1969). The gamma intensities of the aforementioned isotopes were quantified for this application via the Los Alamos National Laboratory (LANL) ENDF database and the beta emissions with the BSPEC subroutine.

## Geometry

The beta exposure to the skin or eyes of a person in a radiation field is a geometrically complex phenomenon due to the varied topologies of the body and surface

sources, which change with time as the individual transits, occupies or performs tasks in that field. Nevertheless, as demonstrated in the following section, reasonable estimates of doses from exposures to large, uniform radiation fields can be obtained by applying one-dimensional (i.e., planar) transport techniques, thus allowing the analysis to be performed in a computationally efficient manner. The simplified geometric configuration assumed in the analysis of beta skin dose from exposure to mixed fission products is depicted in Fig. 3. The planar material layers employed in this model are as follows:

- Soil: A layer of representative material beneath the source that is included to model electron backscatter. Its thickness (26 g $cm^{-2}$) is large compared to the maximum range of a beta particle, and its composition [1% (by weight) hydrogen, 54% oxygen, 13% aluminum, and 32% silicon] is typical of soil at the NTS (Huszar et al. 1977);
- Source: A microscopically thin layer from which the beta particles are isotropically emitted with the Finn energy distributions (modified to include actinide contributions in supplemental calculations);
- Air: Layer of incremental thickness (from 1 cm to 2 m, indicated by "x" in Fig. 3) composed of 20% (by weight) oxygen and 80% nitrogen at a density of 1.15 mg $cm^{-3}$ for exposures at Pacific test sites and 1.05 mg $cm^{-3}$ for exposures at the NTS. The selected densities are representative values for tests conducted at those locations (Alexander 1967);
- Clothing: Layer of 28 mg $cm^{-2}$ material (taken as carbon) included in supplemental calculations to model the attenuating effects of clothing worn during exposure (U.S. NRC 1992). The results presented in the Tables were derived in the absence of clothing (i.e., bare skin);
- Skin: 70-$\mu$m dead layer (indicated by "d" in Fig. 3), 1-$\mu$m active cell layer (where the dose is assessed), and 1-cm backing layer (for backscatter), each composed of 10% (by weight) hydrogen, 25% carbon, 4.6% nitrogen, 59.5% oxygen, 0.3% sulfur, 0.3% chlorine, 0.2% sodium, and 0.1% potassium, at a density of 1.09 g $cm^{-3}$ (Woodard and White 1986); and
- Eye: For beta dose to the lens of the eye, the skin in this geometric model was replaced with a 1-cm thickness of water, and the relevant dose is determined at a tissue depth of 0.3 cm. Attenuating effects of potentially intervening materials, such as glasses and the eyelid, are not included.

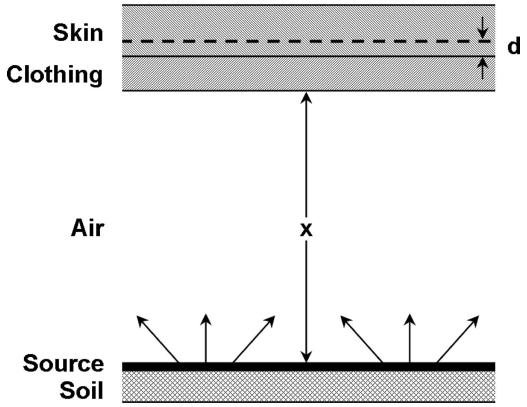

**Fig. 3.** Geometric configuration utilized in skin dose calculations.

To determine the denominator in the beta-to-gamma dose ratio, it is necessary to calculate the free-in-air gamma dose at the height of a properly worn film badge for the gamma source spectrum that corresponds temporally to the beta source spectrum used in obtaining the beta dose in the numerator. A properly worn film badge is one affixed to the external clothing of an individual at chest height, taken here as 137 cm (4.5 feet) above the source plane. The gamma dose calculations employed similar soil, source, and air layers as in the beta dose geometry, but the clothing and skin layers were replaced by a 10-cm air layer in which the dose was calculated, and a 200-m layer of air above the dose layer to ensure that backscatter was adequately characterized.

For analysis of exposures to soil activation products, the source region was modeled differently from that described above. Unlike fallout deposited on a surface, neutron activation products are distributed at depths in the soil. Hashizume et al. (1969) indicates (in his figure 7) that the activation products from a low air burst were distributed approximately uniformly throughout the top 26 g $cm^{-2}$ of soil. Because a layer of this thickness contributes all of the beta particles and nearly all of the gammas escaping from the surface, it is assumed in the present formulation that each of the activation products was uniformly distributed to such depth.

## Computational method

The radiation transport (dose) calculations were accomplished with two codes developed at Sandia National Laboratories: CEPXS/ONEDANT (Lorence et al. 1989) and ITS (the Integrated TIGER Series; Halbleib et al. 1992). While both codes perform coupled electron-photon transport and, in fact, use the same cross section data base, they employ fundamentally different techniques to solve the Boltzmann transport equation: CEPXS/ONEDANT uses the deterministic discrete ordinates method and ITS the stochastic Monte Carlo method. The specific applications of these codes in the assessment are based on computational efficiency. With

a discrete ordinates code, an angular quadrature of order 16 (i.e., the use of 16 angular bins) is sufficient to obtain accurate solutions for the beta sources because of the high degree of electron scattering that takes place in the air between the source plane and the tissue sites of interest. In this case, CEPXS/ONEDANT is more efficient than ITS in obtaining the beta skin doses. However, for the relatively energetic gammas emitted from a fallout source, there is a low occurrence of scattering in the air layer between the source plane and the film badge location. As a result, a quadrature order as high as 128 would be required to obtain accurate results for this case, necessitating lengthy computer runs with CEPXS/ONEDANT. Because ITS is more efficient for treating the gamma fallout sources, the one-dimensional version of that code (ITS TIGER) was used for gamma transport in this analysis.

For neutron-activated soil, CEPXS/ONEDANT is adequate for both beta and gamma dose calculations because of the abundant scattering that takes place in the soil (this was confirmed for gamma by comparison with selected ITS results). To determine the beta-to-gamma dose ratios above neutron-activated soil, the dose contributions from the beta and gamma emissions are first calculated via CEPXS/ONEDANT for each of the relevant activation products and then combined for a given soil type according to their relative radioactivities at the times of interest.

To confirm the adequacy of one-dimensional transport for the present application, the beta skin dose in a 30-cm-diameter cylindrical phantom located in a large, uniform region of 2-d-old fallout was calculated with the three-dimensional version of ITS (ITS ACCEPT). The skin doses thus derived, in units of MeV $cm^2$ $g^{-1}$ per source beta particle, are compared with those from CEPXS/ONEDANT in Fig. 4 as a function of height above the source plane. This comparison demonstrates that the one-dimensional approach provides doses that agree well with those obtained using more sophisticated (and much more computationally intensive) transport techniques.

These computational methods were also verified by comparing dose conversion factors (DCFs, in units of Sv $y^{-1}$ per Bq $cm^{-2}$) derived for surface depositions of specific isotopes with those available in the scientific literature (Kocher and Eckerman 1981). It was observed that the DCFs calculated with CEPXS/ONEDANT for the beta emissions from the isotopes $^{24}$Na, $^{91}$Y, and $^{140}$La are all within 20% of those reported by Kocher (U.S. DOE 1988). Similarly, the DCFs calculated with the ITS code for gamma emissions from these isotopes are within 10% of Kocher's values.

## RESULTS AND DISCUSSION

### Beta-to-gamma dose ratios for bare skin exposure to mixed fission products

The symbol $D_\beta(x,t)$ is used here to denote the beta skin dose for height $x$ above the source plane of mixed fission products at time $t$ after the detonation, as calculated with CEPXS/ONEDANT using the Finn beta spectrum for $t$. Similarly, $D_\gamma(t)$ denotes the corresponding free-in-air gamma dose at the reference film badge height of 137 cm from the source plane, as calculated with ITS

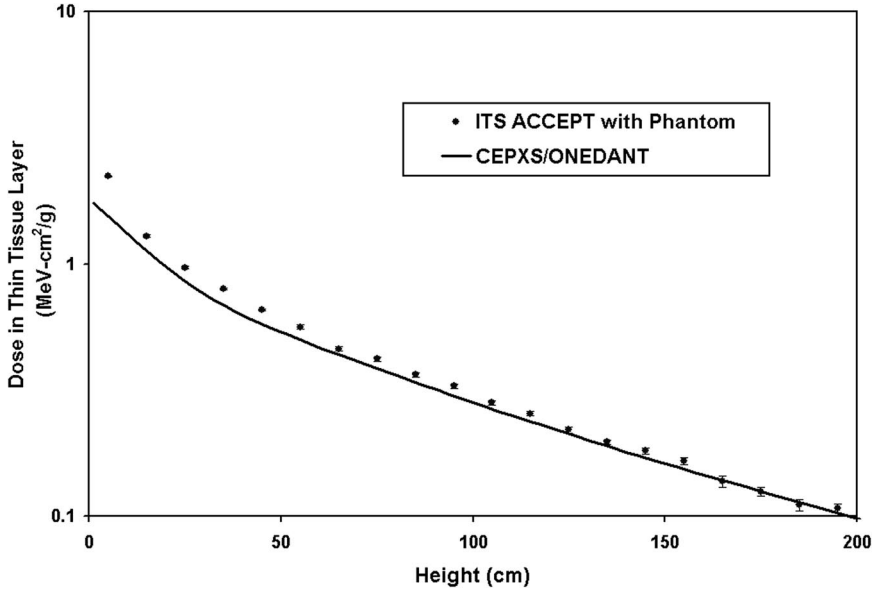


**Fig. 4.** Comparison of beta doses derived using one-dimensional and three-dimensional transport techniques.