DEFENSE THREAT REDUCTION AGENCY

NUCLEAR TEST PERSONNEL REVIEW PROGRAM

RADIATION DOSE ASSESSMENT

Standard Method

ED02 - Whole Body External Dose - Reconstruction

Revision 1.3

Key to SOP ID Codes

RA (Radiation Assessment - SOP)
ED (External Dose - Standard Methods)
ID (Internal Dose - Standard Methods)
UA (Uncertainty Analysis - Standard Methods)

Revision Control

Revision	Revision Description	Revision Date	Authorization Official
1.0	Original	10/31/2007	Paul K. Blake
1.1	- Attachments 1 and 2 are removed. All references to these attachments now refer to Appendices B–C.	03/31/2008	Paul K. Blake
1.2	- Included discussion of intensity calculator function and methods to interpolate early time intensity data. - Minor editorial changes.	10/31/2008	Paul K. Blake
1.3	- Expanded dose model equations to include used in probabilistic approach. - Expanded formulation of protection and shielding factors. - Expanded section of time dependence of intensity. - Expanded section on dose from neutron activation products. - Added default input parameter table as Attachment 1. - Added references. - Minor editorial changes.	01/31/2010	Paul K. Blake

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Standard Method

ED02 – Whole Body External Dose - Reconstruction

1 Purpose/Summary

Standard Method (SM) ED02, *Whole Body External Dose – Reconstruction*, provides methods and techniques for assessing the whole body external doses to nuclear test participants for the Nuclear Test Personnel Review (NTPR) Program according to the procedures specified in standard operating procedure (SOP) RA01. Whole body external doses include those resulting from exposures to initial neutron and gamma radiation and to residual gamma radiation from radioactive materials external to the body.

2 Scope

This standard method provides technical guidance for reconstructing, in accordance with the requirements of Title 32, Code of Federal Regulations, Part 218, *Guidance for the Determination and Reporting of Nuclear Radiation Dose for DoD Participants in the Atmospheric Nuclear Test Program*, the whole body doses that resulted from external neutron and gamma radiation sources encountered by nuclear test participants. It is intended primarily for use by dose reconstruction analysts working in the NTPR Program. It also provides formal documentation of these methods and techniques for internal and external reviewers of the Program. Additional operation-specific data and information for whole body external dose reconstruction is provided in Appendices A–C of this NTPR SOP Manual and references therein. The uncertainties associated with the reconstructed whole body external doses are discussed in SM UA01.

3 Responsibilities

It is the responsibility of dose reconstruction analysts to understand and correctly apply the methods and techniques presented below. If situations arise where these methods and techniques are inadequate to address a specific exposure scenario, it is the responsibility of the analyst encountering this deficiency to bring it to the attention of the SOP Task Manager so that the methodology can be extended as required to provide adequate estimates of whole body external doses. It is the responsibility of the staff member executing and implementing this extension to document such in a revision to this standard method.

4 Definitions

Film Badge Dosimeter (Film Badge): A device containing a packet of photographic film contained within a holder/filter combination used to measure radiation exposure for the purpose of personnel monitoring.

Initial Nuclear Radiation: Neutrons and gamma radiation emitted from the fireball and the cloud column during the first minute after a nuclear explosion.

Neutron Activation: Radioactivity produced in certain materials as a result of nuclear reactions induced in those materials by neutrons, resulting in the formation of unstable isotopes.

Residual Nuclear Radiation: Nuclear radiation emitted from fission products and other debris at times greater than 1 minute after a nuclear detonation.

5 Method Description

Whole body external dose results from exposure to radiation sources outside the body whose emissions are sufficiently penetrating so as to deposit energy throughout the body. The specific emissions of concern here are neutrons and gamma rays. Whole body external dose is distinct from skin or eye dose, which is the dose delivered to the skin or eye of an individual by both penetrating and non-penetrating (primarily beta) radiations (addressed by SMs ED03, ED04, and ED05), and from internal dose, which is dose delivered by radiation sources inside the body (SM ID01). The gamma component of whole body external dose was frequently measured by an individual film badge affixed to the external clothing of a participant; film badge dosimetry for nuclear test participants is discussed in SM ED01. In the absence of film badge data, or if the validity of such data is suspect due to damage to the film medium, it is necessary to reconstruct the gamma dose based on knowledge of the radiation environment and the participant's interaction with that environment. Almost all neutron doses must be reconstructed because film badges were insensitive to neutrons. This standard method addresses the methods and techniques used to reconstruct whole body external doses for nuclear test participants. The values of the input parameters for the deterministic models and parameter distributions used in the probabilistically-based analyses are given in Attachment 1.

5.1 Initial Radiation

As indicated above, the neutrons and gamma radiation emitted during the first minute after a nuclear detonation constitute the initial radiation. Doses from initial radiation emitted from even the largest U.S. detonations were not measurable at distances greater than about 11 kilometers (7 nautical miles) for personnel at or near ground or sea level because of absorption of the radiation by the atmosphere and geometric dispersal with distance from the source (r^{-2} effect) (Glasstone et al., 1977, pp 353-386). For most nuclear tests, the distances at which the dose from initial radiation becomes negligible are much smaller. Care must be taken, however, when assessing initial doses to personnel who are airborne at the time of detonation, as the reduced density of the air with altitude allows these radiations to propagate farther than through air at ground or sea level. A listing of previously determined initial doses was complied by Weitz and Egbert (2009).

5.1.1 Initial Neutron Radiation Dose

More than 99 percent of the neutrons produced in a nuclear detonation are emitted in the first microsecond (10^{-6} s) after detonation. The propagation of these "prompt" neutrons outward from the point of origin is a complicated physical process. Thus, the reliable reconstruction of the neutron doses to personnel in the vicinity of a nuclear detonation generally requires the use of radiation transport techniques coupled with knowledge of the neutron output spectrum for the nuclear device and of the surrounding physical environment. Such a calculation effort is not warranted for the vast majority of nuclear test participants, however, because they were located at distances sufficiently far from the detonation point that their neutron doses were immeasurably small. A study was performed in 1984-85 to screen the various units that participated in nuclear tests to identify those personnel who may have received neutron doses of 0.001 rem or greater (Goetz et al., 1985). It is concluded from this study that the following personnel received neutron doses less than 0.001 rem:

Continental United States (CONUS): (1) All participants of Project (Operation) TRINITY, and (2) for all personnel who, at the times of the detonations at the Nevada Test Site (NTS), were located at News Nob, the nearby Control Point, Yucca Flat Airstrip, Camp Mercury, Camp Desert Rock, and Indian Springs Air Force Base.

OCEANIC: All personnel located on land or aboard ship at the times of detonation.

Conversely, the study identified 160 units or projects as possibly having received neutron doses exceeding 0.001 rem. Of these, approximately 75 percent are aircrews and the remainder ground-based units. These units or projects (minus those that have subsequently been shown to have had neutron doses less than 0.001 rem) are provided in the operation-specific sections of Appendices B and C of this manual and in Weitz and Egbert (2009). Neutron doses that have been calculated for those exposures or, in the case of Operation HARDTACK I, that are indicated by sulfur packet measurements made aboard aircraft, are included in these tabulations. Doses listed for personnel who were in trenches at the time of detonation were derived by modeling this geometry in the radiation transport calculation. (Note: All neutron doses taken from Goetz et al. (1985) or later assessments have been multiplied by a factor of 2 for inclusion in Appendices B and C, in accordance with the recommendation made in Kocher (2007). This adjustment accounts for the difference between the radiation weighting factor of 20 now recommended by ICRP for neutrons (ICRP, 1991) and the mean quality factor of 10 used in the original calculations.)

For participants in units/projects for which neutron doses are not provided, scenario-specific calculations are required to reconstruct these doses. In most scenarios of interest, almost the entire neutron dose is delivered within a fraction of a second after the detonation. The recipient of that dose can be considered stationary during its deposition, thereby simplifying the calculation. Version 6 of the Air Transport of Radiation code (ATR6) code (Kaul et al., 1992) may be used with device- and scenario-specific input data to provide estimates of free-field neutron doses. For scenarios involving other than free-field exposures (e.g., troops in a trench), more sophisticated radiation transport codes, such as MCNP (Briesmeister, 2000), are required.

5.1.2 Initial Gamma Radiation Dose

The initial gamma radiation emitted by a nuclear device detonation consists of three components:

- Prompt gamma—gamma rays produced directly by the fission process and emitted within 10^{-7} s of the detonation.
- Secondary gamma—gamma rays produced by the inelastic scattering and capture of neutrons by the nuclei of atoms in the air and ground, emitted from 10^{-7} s to 10^{-1} s after detonation.
- Fission product or debris gamma—gamma rays from the radioactive decay of fission products and other debris from the device, emitted up to 1 minute after the detonation to include gamma rays from short lived isotopes that would have decayed within that first minute.

The reconstruction of doses from the prompt and secondary gamma radiation components are amenable to standard radiation transport techniques using appropriate neutron and gamma weapon output spectra (available in various references, some of which are classified). However, calculation of the dose from fission product or debris gamma radiation is complicated by three factors:

- The movement of the radiation source (fireball) as it rises in the atmosphere.
- Hydrodynamic enhancement (a dose enhancement caused by a decrease in the attenuation of fission product gamma rays emitted after the passage of the positive phase of the shock wave as the radiation propagates through low density air).
- Possible movement of personnel (e.g., those flying in an aircraft) during the time interval that debris gamma radiation is being emitted.

In most cases, the doses from initial gamma radiation can be adequately calculated with the ATR6 code mentioned above. This code addresses each of the three initial gamma components separately, and the algorithm used for the fission product gamma component accounts for the movement of the fireball and hydrodynamic enhancement effects. The code calculates doses for stationary targets and can be used to reconstruct the fission product gamma dose to personnel in an aircraft flying in the vicinity of the rising fireball. However, more elaborate transport techniques must be applied to reconstruct doses to personnel whose shielding configuration changes significantly shortly after the detonation. These include, for example, volunteer observers who emerged from a trench after the shock wave had passed their position.

Due in large part to the complications outlined above with respect to determining the fission product gamma dose, it is more difficult to define bounding distances beyond which the initial gamma dose can be considered negligible. Consequently, no comprehensive screening has been performed for initial gamma doses as was done for initial neutron doses. However, based on data provided in Glasstone et al. (1977, pp. 353–386) and the known distances of personnel from the shots, it can be stated with confidence that the participants in the oceanic test series who were present on land or aboard ship at the times of detonation received initial gamma doses of less than 0.001 rem. For the CONUS test series, an extensive number of calculations have been performed and documented on the initial gamma doses to participating units (Goetz et al., 1980 and 1981; Frank et al., 1981). Available initial gamma doses are provided in the operation-specific sections of Appendices B and C. For cases where initial gamma dose reconstructions are not available, specific ATR6 or other calculations may be required to obtain them.

5.2 Residual Gamma Radiation Dose

Residual gamma radiation is that gamma radiation emitted in the radioactive decay of fission products, neutron-activated products, and other nuclear device debris 1 minute or more after the detonation. Very few neutrons are emitted in this timeframe. The most commonly encountered source of residual gamma radiation is fallout, but test participants were also exposed to gamma radiation emitted from activation products in the soil or on target ships, contaminants in water, or contaminants encountered by aircraft flying near or through radioactive clouds. Reconstructions of doses from these sources are addressed in the following sections.

5.2.1 Surface-Deposited Fallout

Fallout was the prevalent source of exposure for most nuclear test participants. The geographical pattern of the fallout field was influenced primarily by the direction and magnitude of the prevailing winds above the test site. At NTS, test participants operated in both freshly deposited and aged fallout at the site, and occasionally resided in camps that received light fallout. Personnel who participated in the oceanic tests encountered both fresh and aged fallout on residential and recreational land areas and on ships supporting the operation. The fallout fields are characterized by radiation intensity measurements taken at specific times and locations after the detonation. The intensities at later times can be readily estimated because fallout decays in a predictable manner.

For CONUS tests, monitors conducted radiological surveys shortly after virtually all of the shots, documenting intensities at specified times and locations (Hawthorne, 1979). Thus, the radiation intensities in the vicinities of these shots are relatively well known from several post-detonation surveys and can be estimated for later times using time decay functions as indicated above.

A test participant walking through or operating in a residual radiation fallout field experienced radiation intensities that varied in time due to the movement through the non-uniform field and radiological decay in time. The whole body gamma dose from moving and operating in a fallout field is given by:

$$D_\gamma = F_B \int_{t_{start}}^{t_{end}} I(t,\vec{r}(t))\, dt \tag{1}$$

where

D_γ	=	Whole body external gamma dose (rem)
$I(t,\vec{r}(t))$	=	Free-field intensity at a participant's time-varying location $\vec{r}(t)$ at time t (R hr^{-1})
F_B	-	Film badge conversion factor (rem R^{-1})
t_{start}	=	Start time of exposure to external radiation (hr)
t_{end}	=	End time of exposure to external radiation (hr)

The film badge conversion factor (F_B) is the ratio of dose recorded on a properly worn film badge to free-in-air integrated intensity. This factor, which accounts for body shielding of the film badge to gamma radiation, has been assigned the deterministic values of 0.7 for the standing position in a planar fallout field and 1.0 for one facing the source of radiation (e.g., a contaminated aircraft during an examination) The integration in Equation 1 must often be performed numerically since $I(t,\vec{r}(t)$ generally cannot be integrated in analytical form.

In many scenarios of interest, a test participant remained in a fallout field with little spatial variation of intensity for significant periods of time. This occurred for NTS and oceanic participants whose residential or recreational areas were contaminated by fallout, and for oceanic participants who resided on ships that received topside fallout. In these cases, a spatial average intensity was recorded and the intensity function in Equation 1 takes the simplified form $I(t)$, indicating that it does not depend on the participant's movement within the field.

The functional dependence of fallout intensity on time can be specified in various ways. For the time interval during which fallout was descending, time-intensity data pairs are often available. These early-time intensity data are modeled by applying a curve fitting algorithm to produce an "early time intensity function" denoted by $I_{early}(t)$ in this application. Mathcad®, the principal computational platform used for NTPR dose reconstruction, offers a number of options for functional fitting of data sets. Linear interpolation in logarithmic space is often used for the early-time intensity function. In Mathcad syntax, this takes the form:

$$I_{early}(t) = 10^{\text{linterp}[T, \log(EarlyI),\ t]} \qquad (2)$$

The right side of Equation 2 is simply 10 raised to the power of the base-10 logarithm of the intensity at time t, as linearly interpolated ("*linterp*") from the time-intensity data pairs in Table 1. T is the time array (t_0, t_1, t_2) and *EarlyI* is the intensity array (I_0, I_1, I_2) of the measured time-intensity pairs.

Following the end of deposition, the time variation of the radiation intensity of the fallout can be approximated as $t^{-\lambda}$, where t is the time after detonation in hours and λ is constant over a specified period of time (Glasstone and Dolan, 1977). The most frequently used values of λ are 1.2 for the first 6 months (4380 hr) after detonation and 2.2 thereafter. However, the decay of fallout material from specific shots is sometimes better characterized by other values of λ as described in Appendices A–C. The lack of information on removal mechanisms such as weathering, decontamination, or remediation requires approximations of λ to neglect these factors. The non-consideration of removal mechanisms causes the intensity to diminish at a slower rate than if leaching, dispersal, or removal of the contaminants were considered. As a result, the use of these parameters generally results in high-sided dose estimates.

Occasionally, multiple values of λ, each applicable for a specified period of time, are used to better quantify the time variation of the post-deposition fallout intensity for specific shots. An example is given in Table 1 to demonstrate the use of multiple λ and how to construct the function $I_{early}(t)$ (Figure 1):

Table 1. Example of Early Time Intensity Data

Time after Detonation (t, in hr)	**Measured Intensity (*EarlyI*, in R hr^{-1})**
$t < t_0$	*0*
t_0	I_0
t_1	I_1
t_2	I_2
t_3	I_3
t_4	I_4

In this example, time t_3, found in Table 1 and Table 2, corresponds to the time of peak intensity, and t_4, found in Table 1, corresponds to the last early time intensity. Time t_5, found in Table 2, corresponds to the end of the operational period; this time is often used to define a period for use of a unique decay constant (λ_2), so determined such that when used, legacy tabulations of intensity measurements can be matched.

Table 2. Example Using Multiple Decay Exponents

Time Interval (hr)	Decay exponents λ_i
t_3 to t_5	λ_1
t_5 to 4380	λ_2
$t > 4380$	2.2

The pre- and post-deposition intensity parameterizations can be combined into a piecewise single intensity calculator function, *ICF(t)*, which is applicable for all times. The intensity calculator function for using the generic parameters in Table 1 and Table 2 can be expressed as:

$$ICF(t) = \begin{cases} 0 & \text{if } t < t_0 \\ I_{early}(t) & \text{if } t_0 \le t < t_3 \\ I_3(t_3/t)^{\lambda_1} & \text{if } t_3 \le t < t_5 \\ I_3(t_3/t_5)^{\lambda_1}(t_5/t)^{\lambda_2} & \text{if } t_5 \le t < 4380 \\ I_3(t_3/t_5)^{\lambda_1}(t_5/4380)^{\lambda_2}(4380/t)^{2.2} & \text{if } t \ge 4380 \end{cases} \quad (3)$$

A plot of *ICF(t)* (solid black curve) overlaid on early-time measured intensity data (squares) is shown in Figure 1 for the following time/intensity pairs, which specify the intensity on Parry Island, Enewetak Atoll, caused by fallout from Operation GREENHOUSE Shot EASY:

$t_0 = 17$ hr　　$I_0 = 0.0001$ R hr^{-1}

$t_1 = 20$ hr　　$I_1 = 0.00035$ R hr^{-1}

$t_2 = 22$ hr　　$I_2 = 0.00065$ R hr^{-1}

$t_3 = 24$ hr　　$I_3 = 0.001$ R hr^{-1}

$t_4 = 30$ hr　　$I_4 = 0.00085$ R hr^{-1}

The function *ICF(t)* in Figure 1 was decayed using $\lambda_1 = 1.1$ for the interval from t_3 to t_5 ($t_5 = 978$ hr), $\lambda_2 = 1.2$ for the interval t_5 to 4380, and $\lambda = 2.2$ thereafter. Note that in this example, the last early time/pair (t_4/I_4) is not used to define *ICF(t)* because it occurs after the peak intensity time.

Given an intensity calculator function, *ICF(t),* for a particular shot and location, the external gamma dose can be calculated as:

$$D_\gamma = F_B \; EDM \int_{t_{start}}^{t_{end}} ICF(t)\, dt \qquad (4)$$

where

ICF(t)	=	Intensity calculator function (R hr^{-1})
EDM	=	External dose multiplier (dimensionless)

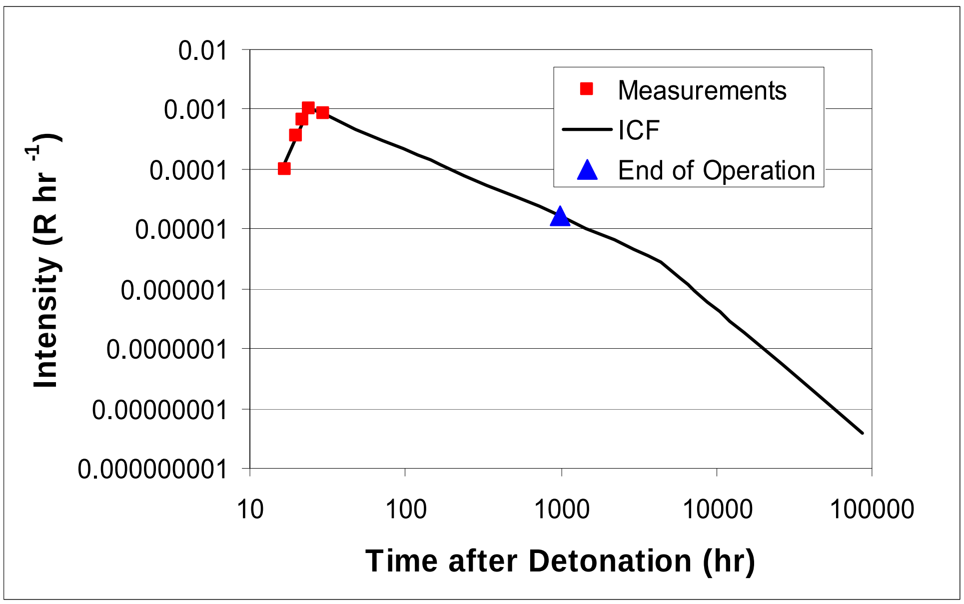

Figure 1. *ICF(t)* and Early Time Intensity Data

Equation 4 is used for a participant who was present at the fallout site from t_{start} to t_{end}. The EDM is used to account for any shielding or protection that the veteran may have had due to being indoors on land or below deck on a ship. If more than one shot contributed to the fallout, the dose from each contributing shot must be calculated and the increments added to get the total whole body dose. EDM for deterministic models is given by the following equations:

$$EDM = \begin{cases} F_o + \dfrac{(1 - F_o)}{PF} & \text{for land - based paricipants} \\ F_{ts} + SF\,(1 - F_{ts}) & \text{for ship - based paricipants} \end{cases} \qquad (5)$$

where

F_o	=	Average fraction of time the participant spent outside
F_{ts}	=	Average fraction of time the participant spent topside
PF	=	Protection factor for land based structures
SF	=	Shielding factor for ships

The use of an EDM assumes that no specific knowledge exists of where the veteran was at any particular time, and is therefore based on distributions around average central values for times spent inside and outside. If the exact location of the veteran is known specific to an occurrence of descending fallout or any other operation that could lead to higher radiation exposures, the EDM would need to be reconsidered and perhaps modified.

For dose assessments using probabilistic methods, shielding afforded the participant by a land-based structure are accounted for with an EDM given by the following equation (Weitz et al., 2009):

$$EDM = F_{os} \cdot I_1 + (1 - F_{os}) \cdot \left[\frac{F_t}{PF_t} \cdot I_2 + \frac{(1 - F_t)}{PF_b} \cdot I_3 \right] \tag{6}$$

where

F_{os}	=	Fraction of time the participant spent outside
F_t	=	Fraction of time the participant spent inside a tent
PF_t	=	Protection factor for a tent
PF_b	=	Protection factor for a building
I_1, I_2, I_3	=	Intensities drawn from a distribution that characterizes the variation in outside intensities

The values of the input parameters for the deterministic models and parameter distributions used in the probabilistically-based analyses are given in Attachment 1.

For dose assessments using probabilistic methods, shielding afforded the participant by the superstructure of a ship are accounted for with an EDM given by the following equation (Weitz et al., 2009):

$$EDM = F_{ts} \cdot I_1 + \left(\frac{1 - F_{ts}}{2} \right) \cdot \left[SF_w \cdot I_2 + SF_b \cdot I_3 \right] \tag{7}$$

where

F_{ts}	=	Fraction of time the participant spent topside
F_w	=	Fraction of time the participant spent at the veteran's work location
F_b	=	Fraction of time the participant spent at his veteran's billeting location
SF_w	=	Shielding factor for the veteran's work location
SF_b	=	Shielding factor for the veteran's billeting location
I_1, I_2, I_3	=	Intensities drawn from a distribution that characterizes the variation in topside intensity

The values of the input parameters for the deterministic models and parameter distributions used in the probabilistically-based analyses are given in Attachment 1.

5.2.2 Activated Sources

For shots at NTS that were detonated at altitudes such that the neutrons reached the surface but the fireball did not, the residual radiation field was mapped with nearly circular iso-intensity contour lines around ground zero. These indicate neutron activation of the soil with peak intensity at ground zero with a strong gradient as one moves away from ground zero in any direction. These contours were measured by radiation monitors shortly after the detonations and are documented in Hawthorne (1979). Doses to personnel who traversed the activated area can be determined by evaluating Equation 1 above, but the decay law given by Equation 3 above no longer applies. An accurate determination of the intensity of an activation field as a function of time requires knowledge of the elemental constituents of the soil in the vicinity of the burst, the neutron absorption cross sections of these constituents, the decay properties of the activation products, and the attenuation of the emitted radiation by the soil. This analysis can be performed in a spreadsheet, supplemented by a limited number of radiation transport calculations. In this manner, it is found that sodium-24 (^{24}Na, half-life = 15 hr) was the dominant radioisotope in the first two days after a detonation over typical NTS soil. Other activation products relevant for NTS exposures include manganese-56 (^{56}Mn, half-life =2.6 hr) and potassium-42 (^{42}K, half-life = 12.4 hr).

To determine the intensity due to exposure from sodium-24, manganese-56, and potassium-42 in the first hours after detonation, it is required to determine the intensity at time-zero t_0 (H+0) intensity based on normalized radiation intensity. Using a measured intensity at a known time T, the zero time intensity is then calculated by:

$$I(0) = \frac{I_T}{0.668 \cdot e^{-\lambda_{Na} T} + 0.274 \cdot e^{-\lambda_{Mn} T} + 0.058 \cdot e^{-\lambda_K T}} \qquad (8)$$

where

$I(0)$	=	Normalized zero-time gamma radiation intensity due to the principal soil activation products (R hr^{-1})
I_T	=	Gamma radiation intensity (R hr^{-1}) observed at measurement time T (hours after the detonation that produced the activated field)
T	=	Time after the detonation when I_T was measured (hr).
λ_{Na}	=	Decay constant for ^{24}Na [l 0.0462 hr^{-1}]
λ_{Mn}	=	Decay constant for ^{56}Mn [0.265 hr^{-1}]
λ_K	=	Decay constant for ^{42}K [l0.056 hr^{-1}]

Having normalized the activation product gamma radiation intensity, the intensity at any elapsed time t) is given by:

$$I(t) = I(0)\left(0.668 \cdot e^{-\lambda_{Na} t} + 0.274 \cdot e^{-\lambda_{Mn} t} + 0.058 \cdot e^{-\lambda_K t}\right) \tag{9}$$

where

$I(t)$	=	Time-dependent intensity from the principal neutron activation products (R hr^{-1})

See Appendix C-7, Attachment C-7-1 for a more complete explanation. Equation 9 should not be used for time less than one hour after detonation (H+1) due to the omission of short-lived neutron activation products such as aluminum-28.

The activation of naval vessels is assessed in Weitz et al. (1982) with regard to exposures to neutron-activated target ships following Shot ABLE of Operation CROSSROADS. It was found that the dominant radioisotope formed on these ships was copper-64 (^{64}Cu, half-life = 12.8 hours). Decay functions for representative ship types are available in Appendix B-1.

The activation of seawater in the Bikini lagoon at Shot ABLE of Operation CROSSROADS is assessed in Weitz et al. (1982). The dominant radioisotope formed was sodium-24. Individuals aboard ships located in the lagoon following the ABLE detonation were exposed to this residual radiation.

5.2.3 Contaminants Adhering to Naval Vessels

It was observed during Operation CROSSROADS and subsequent oceanic operations that ships operating in fallout-contaminated water accumulated radioactive materials on their underwater hulls and in salt water piping and evaporators. The physical processes responsible for this radioactive accumulation appear to include assimilation of radionuclides by aquatic organisms (e.g., algae and barnacles) that were or became attached to the ship, and ion-exchange absorption of the polyvalent fission products by inert material (e.g., paint or rust) on the ship's hull and in the piping. A detailed analysis of this contamination source is presented in Weitz et al. (1982) along with an algorithm for estimating doses to personnel resident on contaminated ships. Based on this model, the intensity of the contaminated hull quickly approached a saturation value given by:

$$I_{hull}(t) = S\,t^{-1.3} \tag{10}$$

where

$I_{hull}(t)$	=	Time dependent saturation intensity on the hull of a ship (R day^{-1})
S	=	Constant on the order of 1.6 R-$\text{day}^{0.3}$ that depends somewhat on ship type. (Weitz et al., 1982)
t	=	Time after detonation (day)

The average intensity in the spaces of the ship below deck is related to the ship's hull intensity by an apportionment factor F_a that depends on the ship's dimensions:

$$I_{belowdeck}(t) = F_a I_{hull}(t) \tag{11}$$

where

$I_{belowdeck}(t)$	=	Time dependent intensity below deck from hull contamination (R day^{-1})
F_a	=	Apportionment factor (Weitz et al., 1982)

As examples, F_a equals 0.39 for a destroyer, 0.05 for a cruiser and 0.10 for a light aircraft carrier. The engine room is estimated to have had an intensity 1.5 times the hull intensity, so personnel with engineering ratings received larger doses than those with non-engineering ratings. The dose from hull contamination would then be calculated using Equation 1 above.

5.2.4 Swimming in Contaminated Water

It is occasionally necessary to reconstruct the external gamma dose for a nuclear test participant who swam in fallout-contaminated or neutron-activated seawater.

5.2.4.1 Fallout-Contaminated Seawater

The external dose due to swimming is related to the exposure measurements above the water. From measurements taken in fallout-contaminated water during Operation

CROSSROADS (Weitz et al., 1982, p. 40), the activity in water and the relationship to the intensity above the water was determined. The dose to a swimmer as related to the intensity above the water is given by:

$$D_\gamma = 0.84\, I_{ff}\, \Delta t \tag{12}$$

where

D_γ	=	External gamma dose accused by a swimmer (rem)
I_{ff}	=	Free-field gamma intensity I_{ff} immediately above the surface of the water (R hr^{-1})
Δt	=	Duration of swimming (hr)

Equation 12 includes the factor of 0.7 to make the dose equivalent to the film badge dose and assumes that the density of tissue is 1 g cm^{-3}.

5.2.4.2 Neutron-Activated Seawater

As indicated earlier, ^{24}Na is the dominant radioisotope produced in seawater by a low-altitude nuclear detonation (Weitz et al., 1982, p. 19). The gamma dose accrued by a swimmer from the ^{24}Na activity while swimming in neutron-activated seawater is:

$$\mathrm{D}_\gamma = 1.65\, \mathrm{I}_{ff}\, \Delta t \tag{13}$$

Equation 13 includes the factor of 0.7 to make the dose equivalent to the film badge dose and assumes that the density of tissue is 1 g cm^{-3}.

5.2.5 Aircraft-Related Exposures

Personnel who flew in cloud sampling, cloud tracking, weather monitoring, or other support aircraft may have been exposed to radiation from the radioactive cloud from contaminants that adhered to or entered the aircraft while flying through or under the cloud, or from fallout or activation products on the ground while flying at low altitude. Fortunately most pilots and other crew members of aircraft susceptible to radiation exposure were provided with film badges to record their doses. In cases where film badge data are unavailable, the methods used in dose reconstruction are strongly scenario-dependent, making it difficult to present generalized approaches.

A more frequently encountered scenario involving lack of film badge coverage relates to ground personnel who were tasked to decontaminate or perform maintenance on aircraft that had flown through airborne contamination and thereby became contaminated. Often the radiation intensities of the surfaces and engines of these aircraft were measured after landing at several time intervals. If such intensity information is available or can be estimated from measurements made under similar circumstances on similar aircraft, the reconstruction of the participant's dose is straightforward. If an intensity $I(t_m,r_m)$ was measured at time t_m from a distance r_m from the contaminated surface, and if the participant was exposed for a period Δt at time t_e and at a distance r_e, his reconstructed dose is given by:

$$D_\gamma = f(r_m,r_e)\,I(t_m,r_m)\,(t_e/t_m)^{-\lambda}\,\Delta t\,. \tag{14}$$

In this expression, the function $f(r_m,r_e)$ relates the magnitude of the intensity at distance r_e to that at distance r_m. If the dimensions of the contaminated area are large compared to r_m and r_e, then $f \sim 1$; this approximates an infinite plane of contaminated material. If the dimensions of the contaminated area are small compared to r_m and r_e, then $f \sim (r_m/r_e)^{-2}$; this approximates a point source. Most cases fall somewhere between these two extremes and the appropriate function should be derived by radiation transport techniques for specific cases. Note that the film badge conversion factor of 0.7 is omitted in this case because most of the participant's exposure would have occurred while he was facing the source of radiation.

6 Data and Input

The values of the input parameters for the deterministic models and parameter distributions used in the probabilistically-based analyses are given in Attachment 1. Operation-specific information relevant to the reconstruction of whole body external doses including initial and residual radiation is contained in Appendices A–C.

7 Referenced SOPs and Standard Methods from this Manual

(1) SOP RA01 - Radiation Dose Assessment for Cases Requiring Detailed Analysis

(2) SM ED01 - Film Badge Dose Assessment

(3) SM ED03 - Skin Dose from External Sources

(4) SM ED04 - Skin Dose from Dermal Contamination

(5) SM ED05 - Dose to Lens of Eye

(6) SM ID01 - Internal Organ Doses

(7) SM UA01 - Dose Uncertainty

8 Reference Materials

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Attachment 1 Distributions and Deterministic Values for Model Parameters for External Dose Assessments

The values of input parameters to the external dose models (presented in this SM) provided in Table 1-1 are default numbers that are applicable in most cases. They should be adjusted or replaced for cases where veteran-specific data is available. These default parameter values were estimated or derived in Weitz et al. (2009) and other technical basis documents listed in the references section of that document.

The column labeled "Nominal Value for Central Estimation" contains model input values that can be used to calculate the central (best) estimate of a dose. These values are usually based on documented observed data or best estimates, and were used in building the statistical distributions for each uncertain parameter. For numerically-generated distributions, such as $GSMF$, PF_t, PF_b, SF_b, SF_w, etc., nominal values are the central estimates of those distributions, which are based on physical and mathematical models that characterize input parameters and their uncertainty and variability. Calculations of nominal doses provide point estimates using a dose reconstruction model with nominal values for all of its input parameters. In addition, nominal values are used as input parameters for model sensitivity analyses (Weitz et al., 2009)

Table 1-1. Distributions and Deterministic Values for Model Parameters for External Dose Assessments

Parameter	Definition	Distribution for Probabilistic Analysis (*)	Nominal Value for Central Estimation	Deterministic(**)
SCENARIO PARAMETERS				
Dates and Times of Arrival and Departure at Assigned Location				
$Date_{Arrived}$	Start date[time]	Triangular Example min = Jun 19 [0000] mode = Jun 19 [1200] max = Jun 20 [1000]	Jun 19 [1200]	Jun 19 [0800]
$Date_{Departed}$	End date[time]	Triangular Example min = Jul 5 [0000] mode = Jul 6 [1200] max = Jul 6 [0000]	Jul 6 [1200]	Jul 6 [2400]
F_B	Film Badge Conversion Factor	n/a	0.7 for planar source, 1.0 for facing a source	0.7 for planar source, 1.0 for facing a source
PARAMETERS FOR MANEUVER UNITS AT NTS				
ST	Start time of maneuver after detonation	Normal Parameters are case specific	Case specific	Case specific
Rate	Walk rate during maneuver	Triangular Parameters are case specific	Case specific	Case specific
LT	Linger time at Rad-Safe limit location	Triangular Parameters are case specific	Case specific	Case specific
SHOT MIXTURE FRACTION for OPERATION HARDTACK I SHOTS FIR AND KOA				
Fallout Composition	Fallout proportion from each shot (applies to FIR/KOA only)	Triangular min = 0 mode = 0.4 max = 1 for FIR fraction	Intensity based on 0.4/0.6 mixture of FIIDOS-derived FIR/KOA decay functions	Intensity data based on time-dependent decay exponents for FIR/KOA mixture

Parameter	Definition	Distribution for Probabilistic Analysis (*)	Nominal Value for Central Estimation	Deterministic(**)
EXTERNAL DOSE MULTIPLIER (EDM) FOR LAND-BASED PERSONNEL				
F_{os}	Fraction of time spent outside	Triangular NTS Example min = 5/24 mode = 12/24 max = 18/24	0.5 (or 12/24)	0.6 (or 14.4/24)
		PPG Example min = 2/24 mode = 8/24 max = 16/24	0.34 (or 8/24)	0.6 (or 14.4/24)
F_t	Fraction of inside time spent in tent (the remainder of the time spent indoors is assumed to take place in barracks with walls made of metal or wood.)	Triangular min = 0 mode = 0.5 max = 1	0.5	0
I_1, I_2, I_3	Modifier of local gamma radiation intensity relative to the average outdoor intensity when veteran is outdoors (I_1), inside a tent (I_2) and inside a barrack (I_3)	Lognormal GM = 1.0 GSD = 1.5	1.0	1.0
PF_b	Protection factor for building	Numerical model (see Weitz et al. [2009]) Mean = 2.1 95%tile = 3.9	2.0 (median of distribution)	2.0
PF_t	Protection factor for a tent	Numerical model (see Weitz et al. [2009]) Mean = 1.4 95%tile = 1.9	1.4 (median of distribution)	1.5

Parameter	Definition	Distribution for Probabilistic Analysis (*)	Nominal Value for Central Estimation	Deterministic(**)
INTENSITY MEASUREMENTS FOR LAND-BASED PERSONNEL				
I_m	Measured intensities (with errors due to instrument precision, calibration and operator manipulation)	Normal Mean = I_m 95%tile/Mean = (1.5–2.0)	I_m	I_m
Contour intensities *I(t)*	Intensities obtained from iso-intensity plots	See Weitz et al. (2009)	*I(t)*	*I(t)*
a	Exponent of multiplicative error factor $(t/t_0)^{\pm a}$ applied to FIIDOS-generated intensity functions	Normal μ = 0 σ = 0.15	0	0
EXTERNAL DOSE MULTIPLIER (EDM) FOR SHIP-BASED PERSONNEL				
F_{ts}	Fraction of time spent topside	Triangular min = 4/24 mode = 9.6/24 max = 18/24	0.4 (or 9.6/24)	0.4 (or 9.6/24)
I_1, I_2, I_3	Modifier of local gamma radiation intensity relative to the average topside intensity when veteran is topside (I_1), below deck at a work location (I_2) and below deck at in a billet area (I_3)	Post-decontamination numerical model for elliptical ships typical of USS ESTES (see Weitz et al. [2009]) μ = 1.0 σ = 0.70	0.88 (median of distribution)	1.0
I_m	Measured intensities (with errors due to instrument precision, calibration and operator manipulation)	Normal Mean = I_m; 95%tile/Mean = (1.5–2.0)	I_m	I_m
SF_b	Shielding factor at below-deck billet location (assumed on 3rd deck below topside)	Elliptical ship model (see Weitz et al. [2009]) GM = 0.016	0.016	0.1
	Shielding factor at below-deck billet location (assumed equally likely on 3rd or 4th decks below flight deck)	Rectangular ship model (see Weitz et al. [2009]) GM = 0.021	0.021	0.1

Parameter	**Definition**	**Distribution for Probabilistic Analysis (*)**	**Nominal Value for Central Estimation**	**Deterministic(**)**
SF_w	Shielding factor at below-deck worksite (assumed equally likely on 1st or 2nd decks below topside)	Elliptical ship model (see Weitz et al. [2009]) GM = 0.079	0.079	0.1
		Rectangular ship model (see Weitz et al. [2009]) GM = 0.11	0.11	0.1
INTENSITY MEASUREMENTS FOR SHIP-BASED PERSONNEL				
a	Exponent of multiplicative error factor $(t/t_0)^{\pm a}$ applied to FIIDOS-generated intensity functions	Normal μ = 0 σ = 0.15	0	0
I_m	Measured topside intensities (with errors due to instrument precision, calibration and operator manipulation)	Normal Mean = I_m; 95%tile/Mean = (1.5–2.0)	I_m	I_m
I_{sc}	Measured ship contamination intensity (with errors due to instrument precision, calibration and operator manipulation)	Lognormal multiplier GM = 1 95%tile = 3.2	I_{sc}	I_{sc}
I_{ws}	Measured water shine intensity (with errors due to instrument precision, calibration and operator manipulation)	Lognormal multiplier GM = 1 95%tile = 2.4	I_{ws}	I_{ws}

(*) μ = arithmetic mean; σ = standard deviation; GM = geometric mean; GSD = geometric standard deviation;
95%tile = value of the distribution at the 95th percentile.
(**) High-sided per guidance in NTPR Policy and Guidance Manual (DTRA, 2007).