DEFENSE THREAT REDUCTION AGENCY

NUCLEAR TEST PERSONNEL REVIEW PROGRAM

RADIATION DOSE ASSESSMENT

STANDARD METHOD

ED02 – Whole Body External Dose Assessment

Revision 2.0

Cleared for Release

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
2.0	− Edited and expanded Section 5.2.1 and split it into five subsections to improve readability, augment the discussion of GSMF, and clarify the use of measured intensity data points in establishing the intensity calculator function. − Added a table of GSMF values as new Attachment 2. − Revised and moved content as needed to improve flow. − Updated References with new references and current versions, such as revised NTPR Technical Memorandums/Technical Notes. − Editorial changes and corrections throughout as needed.	04/30/2021	James D. Franks

Table of Contents

List of Figures

List of Tables

Standard Method

ED02 – Whole Body External Dose Assessment

1. Purpose/Summary

This Standard Method (SM) 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 following detonation and to residual gamma radiation from radioactive materials external to the body.

2. Scope

This SM provides technical guidance for reconstructing the whole body doses that resulted from external neutron and gamma radiation sources encountered by nuclear test participants. The doses are reconstructed in accordance with the requirements of Title 32, Part 218, Code of Federal Regulations, *"Guidance for the Determination and Reporting of Nuclear Radiation Dose for DoD Participants in the Atmospheric Nuclear Test Program"* (DoD, 2020). The SM 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

Intensity: a legacy term of the NTPR Program which is the same as the free-field radiation exposure rate expressed in units of roentgen per unit of time.

Film Badge Dosimeter (Film Badge): a device containing a packet of photographic film contained within a holder/filter combination used to measure external 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, including fallout (see Section 5.2), 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 lens of the 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 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 value 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 (or approximately 7 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 and Dolan, 1977). 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 compiled by Weitz and Egbert (2010).

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) 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 detonations.

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 SOP manual and in Weitz and Egbert (2010). 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 SOP 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 and Dolan (1977) 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 SOP 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 h^{-1})
F_B = Film badge conversion factor (rem R^{-1})
t_{start} = Start time of exposure to external radiation (h)
t_{end} = End time of exposure to external radiation (h)

If the intensity function can be expressed as a function of time only, as $I(t)$, for a particular shot and known exposure movement, then the external gamma dose can be calculated as shown in Equation 2:

$$D_\gamma = F_B\ EDM\ \int_{t_{start}}^{t_{end}} I(t)\,dt \tag{2}$$

where

$I(t)$ = Intensity as a function of time; see Section 5.2.1.3 for cases where intensity measurement is taken from a nearby location other than the location where a dose estimate is sought (R h^{-1})
EDM = External dose multiplier (dimensionless)

Equation 2 is used for a participant who was exposed to ground-deposited fallout from t_{start} to t_{end}. The EDM parameter 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 unless an intensity measurement is available that simultaneously captures the total exposure rate from all contributing shots. The parameter EDM is discussed in Section 5.2.1.4.

5.2.1.1 Intensity Function

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.

For assessments where a participant's movement and timing are well-documented and the movement occurred in an intensity varying field, it is possible to convert the space and time relationship of the intensity function to a simple function of time. In this case, Equation 2 above can be used. Also, the integration can be approximated with a summation of doses for each segment of the participant movement using an average intensity for each segment or the highest value for each segment.

5.2.1.2 Film Badge Conversion Factor

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 inspection.

5.2.1.3 Use of the Gamma Source Modification Factor (GSMF)

To calculate doses at a location where no exposure rate measurements are available, surrogate data from a nearby location can be used. Use of surrogate data from a nearby location is justified by the assumption of similarity in surface activity density at the location of the measurement and the location where a dose needs to be assessed. The Gamma Source Modification Factor (GSMF) corrects for situations where surfaces contaminated by fallout were not infinite in spatial extent. For land-based applications, the area of fallout deposition was generally large enough that the correction is insignificant. Thus, for exposures to fallout on land, GSMF is 1. However, for shipboard exposures, the deposited fallout was limited to the finite area of the weather deck of the ship and GSMF values are greater than 1. (Weitz, 2010)

For external dose calculations that use exposure rate measurements from a nearby location, the measured rates should be multiplied by the ratio of GSMF for the measurement location to the GSMF for the assessment location. The exposure rate correction is expressed as follows:

$$I(t)=\frac{GSMF_m}{GSMF} I_m(t) \tag{3}$$

where

$I(t)$ = Intensity at location where dose estimate is sought (R h^{-1})
$I_m(t)$ = Intensity at location where measurement was made (R h^{-1})
$GSMF$ = GSMF for the location of dose assessment
$GSMF_m$ = GSMF for the location of intensity measurement

If the ratio $\frac{GSMF_m}{GSMF}$ in Equation 3 is lower than 1, a ratio of 1 may be used as a high-sided value. An example of a GSMF ratio of less than 1 is when exposure rate measurements were made on an island or on a large ship and then used as surrogate data for a small ship or a ship with a large superstructure that provides shielding.

An example of a GSMF ratio greater than 1 is when exposure rate measurements on a nearby ship are used as surrogate data for an island, or measurements from a small ship are used for a larger ship or with less superstructure.

A nominal value of 2 has been typically used for GSMF in internal dose estimation for shipboard personnel assessments. However, results from an improved method developed for probabilistic assessments of shipboard exposures should be used that take into consideration the ship dimensions and the shielding afforded by its superstructure. Except for aircraft carriers, the more explicitly calculated GSMF values are higher than 2. The mean values of GSMF for the deterministic models and distributions parameters used in the probabilistically based analyses are given in Attachment 2. (Weitz, 2010)

5.2.1.4 External Dose Multiplier (EDM)

The external dose multiplier 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:

$$EDM_{land} = F_{os} + \frac{(1 - F_{os})}{PF} \quad \text{for land-based participants}$$
$$EDM_{ship} = F_{ts} + SF\,(1 - F_{ts}) \quad \text{for ship-based participants} \tag{4}$$

where

F_{os} = 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 is accounted for with an EDM given by the following equation (Weitz et al., 2009):

$$EDM_{land} = F_{os} \cdot I_1 + (1 - F_{os}) \cdot \left[\frac{F_t}{PF_t} \cdot I_2 + \frac{(1 - F_t)}{PF_b} \cdot I_3\right] \tag{5}$$

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 decks of a ship are accounted for with an EDM given by the following equation (Weitz et al., 2009):

$$EDM_{ship} = F_{ts} \cdot I_1 + \left(\frac{1 - F_{ts}}{2}\right) \cdot [SF_w \cdot I_2 + SF_b \cdot I_3] \qquad (6)$$

where

F_{ts} = Fraction of time the participant spent topside
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 formulation of Equation 6 assumes that the participant split his below-deck time evenly between his work and billet locations. The values of the input parameters for the deterministic models and parameter distributions used in the probabilistically based analyses are given in Attachment 1.

5.2.1.5 Intensity Calculator Function and Estimation of External Dose

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. The Mathcad software, 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:

$$I_{early}(t) = 10^{\mathrm{linterp}[T, \log(EarlyI),\ t]} \qquad (7)$$

The right side of Equation 7 is simply 10 raised to the power of the base-10 logarithm of the intensity at time *t*, as linearly interpolated ("*linterp*") from time-intensity data pairs. A generic example of the time-intensity pair structure is shown in Table 1. The parameter *T* in Equation 7 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. To establish $I_{early}(t)$, all time-intensity pairs listed in the operation-specific SOP appendix for each operation and shot should be used, when available, even if some of the pairs represent measurements made after the time of peak intensity. This ensures consistency in the data used in the dose reconstructions for all operations.

Table 1. Example of early time radiation time-intensity pairs

Time after Detonation (t, in h)	Measured Intensity (*EarlyI*, in R h^{-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

Following the time of the last measured intensity, 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 the decay exponent 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 h) 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 SOP 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 2 to demonstrate the use of multiple λ values.

Table 2. Example using multiple decay exponents

Time Interval (h)	Decay Exponent λ_i
$t_0 \le t < t_4$	n/a*
t_4 to t_5	$\lambda_1 = 1.1$
t_5 to 4380	$\lambda_2 = 1.2$
$t > 4380$	$\lambda_3 = 2.2$

* In this example, measured intensities are used for this time interval.

In this example (Table 1 and Table 2), the first measurement (I_0) was taken at time t_0, descending fallout continued until the peak measurement at time t_3, and t_4 corresponds to the time of the last early time intensity measurement. Time t_5, found in Table 2, corresponds to the end of the operational period. Time t_5 is assumed to be less than 4380 h post-detonation and 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.

The 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:

$$ICF(t) = \left\{ \begin{array}{ll} 0 & if\ t < t_0 \\ I_{early}(t) & if\ t_0 \le t < t_4 \\ I_4(t_4/t)^{1.1} & if\ t_4 \le t < t_5 \\ I_4(t_4/t_5)^{1.1}(t_5/t)^{1.2} & if\ t_5 \le t < 4380 \\ I_4(t_4/t_5)^{1.1}(t_5/4380)^{1.2}(4380/t)^{2.2} & if\ t \ge 4380 \end{array} \right\} \qquad (8)$$

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 intensities on Parry Island, Enewetak Atoll, caused by fallout from Operation GREENHOUSE Shot EASY:

t_0 = 17 h	I_0 = 0.0001 R h^{-1}
t_1 = 20 h	I_1 = 0.00035 R h^{-1}
t_2 = 22 h	I_2 = 0.00065 R h^{-1}
t_3 = 24 h	I_3 = 0.001 R h^{-1}
t_4 = 30 h	I_4 = 0.00085 R h^{-1}

The function *ICF(t)* in Figure 1 was constructed decayed using $\lambda_1 = 1.1$ for the interval from t_4 to t_5 ($t_5 = 978$ h), $\lambda_2 = 1.2$ for the interval t_5 to 4380, and $\lambda = 2.2$ thereafter (see Table 2).

Once an intensity calculator function, *ICF(t),* is established for a particular shot and location or scenario of exposure, the external gamma dose can be calculated using Equation 2 where *I(t)* is replaced with *ICF(t)* as follows:

$$D_\gamma = F_B\ EDM \int_{t_{start}}^{t_{end}} ICF(t)\,dt \qquad (9)$$

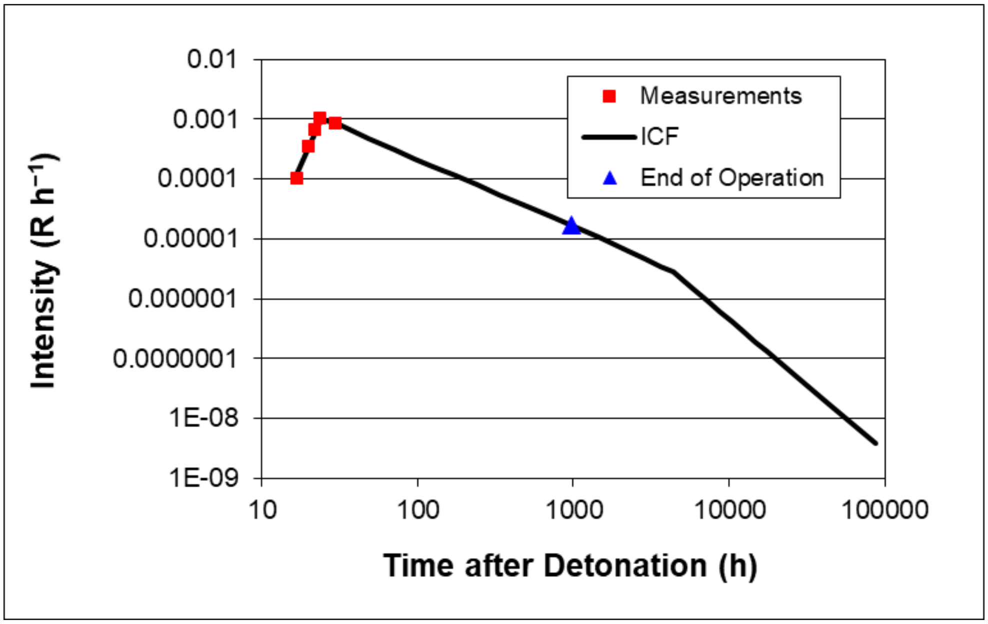

Figure 1. *ICF(t)* and early time radiation intensity plot

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 function given by Equation 8 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 (Na-24, half-life = 15 h) 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 (Mn-56, half-life =2.6 h) and potassium-42 (K-42, half-life = 12.4 h).

To determine the intensity due to exposure from Na-24, Mn-56, and K-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:

$$I(0) = \frac{I_T}{0.668 \cdot e^{-\lambda_{Na} T} + 0.274 \cdot e^{-\lambda_{Mn} T} + 0.058 \cdot e^{-\lambda_K T}} \tag{10}$$

where

$I(0)$ = Normalized zero-time gamma radiation intensity due to the principal soil activation products (R h^{-1})

I_T = Gamma radiation intensity (R h^{-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 (h).

λ_{Na} = Decay constant for Na-24 [l 0.0462 h^{-1}]

λ_{Mn} = Decay constant for Mn-56 [0.265 h^{-1}]

λ_K = Decay constant for K-42 [l0.056 h^{-1}]

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

$$I(t) = I(0)\left(0.668 \cdot e^{-\lambda_{Na} t} + 0.274 \cdot e^{-\lambda_{Mn} t} + 0.058 \cdot e^{-\lambda_K t}\right) \tag{11}$$

where

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

See SOP Appendix C-7, Attachment C-7-1 for a more complete explanation of estimating the radiation intensity from soil activation products. Equation 11 should not be used for times less than one hour after detonation (H+1) due to the omission of short-lived neutron activation products such as aluminum-28 (Al-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 (Cu-64, half-life = 12.8 h). Decay functions for representative ship types are available in SOP 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 Na-24. Individuals aboard ships located in the lagoon following the ABLE detonation were exposed to this residual radiation.

5.2.3 Contaminants Adhering to the Hulls of 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:

$$I_{hull}(t) = S\,t^{-1.3} \tag{12}$$

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:

$$I_{belowdeck}(t) = F_a I_{hull}(t) \tag{13}$$

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.

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), the activity in water and the relationship to the intensity above the water was determined (Weitz, 2012). The dose to a swimmer as related to the intensity above the water is approximated by:

$$D_\gamma = 1.4\, I_{ff}\, \Delta t \tag{14}$$

where

D_γ = External gamma dose accrued by a swimmer during the short duration of swimming Δt (rem)

I_{ff} = Free-field gamma intensity above the water surface from fallout, assumed to be constant over the short duration of swimming Δt (R h^{-1})

Δt = Duration of swimming (h)

The factor 1.4 in Equation 14 incorporates a film badge conversion factor of 0.7 to result in a dose that is equivalent to a film badge dose; it is also based on a tissue density of 1 g cm^{-3}. (Weitz, 2012)

5.2.4.2 Neutron-Activated Seawater

As indicated earlier, Na-24 is the dominant radioisotope produced in seawater by a low-altitude nuclear detonation (Weitz et al., 1982). The gamma dose accrued by a swimmer from the Na-24 activity while swimming in neutron-activated seawater (Weitz, 2012) is approximated by:

$$D_\gamma = 1.4\, I_{ff}\, \Delta t \tag{15}$$

The parameter I_{ff} in Equation 15 represents the above-water intensity due to neutron-activated seawater. The factor 1.4 in Equation 15 incorporates a film badge conversion factor of 0.7 to result in a dose that is equivalent to a film badge dose; it is also based on a tissue density of 1 g cm^{-3}. (Weitz, 2012)

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:

$$D_\gamma = f(r_m,r_e)\, I(t_m,r_m)\,(t_e / t_m)^{-\lambda}\, \Delta t \tag{16}$$

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. Information and data specific to each test series to be used for the reconstruction of whole body external doses are contained in SOP 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 -	Lens of the Eye Dose
(6)	SM ID01 -	Doses to Organs from Intake of Radioactive Materials
(7)	SM UA01 -	Dose Uncertainty and Upper-Bound Dose Determination

8. References

Briesmeister, J.F. (ed.), 2000. *MCNP–A General Monte Carlo N-Particle Transport Code–Version 4B*. LA-13709-M, Los Alamos National Laboratory, Los Alamos, NM.

DoD (Department of Defense), 2020. “Guidance for the Determination and Reporting of Nuclear Radiation Dose for DoD Participants in the Atmospheric Nuclear Test Program (1945-1962).” Title 32, Code of Federal Regulations, Part 218. Washington, DC. July 1.

Frank, G., Goetz, J., Klemm, J., Thomas, C., and Weitz, R., 1981. *Analysis of Radiation Exposure, 4th Marine Corps Provisional Atomic Exercise Brigade, Exercise Desert Rock VII, Operation PLUMBBOB*. DNA 5774F, Defense Nuclear Agency, Washington, DC. June 15.

Glasstone, S., and Dolan, P.J., 1977. *Effects of Nuclear Weapons*. U.S. Department of Defense and U.S. Department of Energy (3rd Edition).

Goetz, J., Kaul, D., Klemm, J., McGahan, J., and Weitz, R., 1980. *Analysis of Radiation Exposure for Troop Observers, Exercise Desert Rock VI, Operation TEAPOT*. DNA 5354F, Defense Nuclear Agency, Washington, DC. July 15.

Goetz, J., Kaul, D., Klemm, J., McGahan, J., and Weitz, R., 1981. *Analysis of Radiation Exposure for Troop Observers, Exercise Desert Rock V, Operation UPSHOT-KNOTHOLE*. DNA 5742F, Defense Nuclear Agency, Washington, DC. April 28.

Goetz, J., Klemm, J., Thomas, C., and Weitz, R., 1985. *Neutron Exposure for DoD Nuclear Test Personnel*. DNA-TR-84-405, Defense Nuclear Agency, Washington, DC. August 15.

Hawthorne, H.A. (ed.), 1979. *Compilation of Local Fallout Data from Test Detonations 1945-1962 Extracted from DASA 1251, Volume I—Continental U.S. Tests*. DNA 1251-1-EX, Defense Nuclear Agency, Washington, DC. May 1.

ICRP (International Commission on Radiation Protection), 1991. *1990 Recommendations of the International Commission on Radiological Protection.* ICRP Publication 60, Ann. ICRP 21(1–3), Pergamon Press, New York, NY.

Kaul, D.C., McGuffin, S., and Dolatshahi, F., 1992. *User's Manual, Personal Computer (PC) Edition, Version 6 of ATR (ATR6)*. DNA-TR-91-163, Defense Nuclear Agency, Washington, DC.

Kocher, D.C., 2007. *Considerations on Estimating Upper Bounds of Neutron Doses to Military Participants at Atmospheric Nuclear Tests*. DTRA-TR-07-3, Defense Threat Reduction Agency, Fort Belvoir, VA. April.

Weitz, R., Stuart, J., Muller, E., Thomas, C., Knowles, M., Landay, A., Klemm, J., and Goetz, J., 1982. *Analysis of Radiation Exposure for Naval Units of Operation CROSSROADS, Volume I—Basic Report*. DNA-TR- 82-05-V1, Defense Nuclear Agency, Washington, DC. March 3.

Weitz, R., Case, D., Chehata, M., Egbert, S., Mason, C., Singer, H., Martinez, D., McKenzie-Carter, M., and Stiver, J. 2009. *Probabilistic Approach to Uncertainty Analysis in NTPR Radiation Dose Assessments*. DTRA-TR-09-13, Defense Threat Reduction Agency, Fort Belvoir, VA. November 1.

Weitz, R.L., 2010. *Formulation of the Gamma Source Modification Factor for Ship-based Applications, Revision 1*. NTPR-TM-09-04(R1), Defense Threat Reduction Agency, Fort Belvoir, VA. November 30.

Weitz, R. and Egbert, S., 2010. *Compilation of Initial Radiation Doses to Atmospheric Test Participants, Revision 1*. NTPR-TM-09-01(R1), Defense Threat Reduction Agency, Fort Belvoir, VA. November 30.

Weitz, R.L., 2012. *External Gamma and Skin Doses from Immersion in Contaminated Water*. NTPR-TM-11-04, Defense Threat Reduction Agency, Fort Belvoir, VA. June 18.

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 A1-1 of this attachment are default numbers that are applicable in most cases. They should be adjusted or replaced for cases where veteran-specific data are 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 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 A1-1. 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 19 [2400]	Jun 19 [1200]	Jun 19 [0800]
$Date_{Departed}$	End date[time]	Triangular Example min = Jul 5 [0000] mode = Jul 5 [1200] max = Jul 5 [2400]	Jul 5 [1200]	Jul 5 [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
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)	$I(t)$	$I(t)$

Parameter	**Definition**	**Distribution for Probabilistic Analysis** [*]	**Nominal Value for Central Estimation**	**Deterministic**[†]
a	Exponent of multiplicative error factor $(t/t_0)^{\pm a}$ applied to FIIDOS-generated intensity functions	Normal $\mu = 0$ $\sigma = 0.15$	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]) $\mu = 1.0$ $\sigma = 0.70$	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
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 $\mu = 0$ $\sigma = 0.15$	0	0

Parameter	**Definition**	**Distribution for Probabilistic Analysis** [*]	**Nominal Value for Central Estimation**	**Deterministic**[†]
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.

[†] For deterministic dose models, high-sided (conservative) parameter values are selected to obtain upper-bound doses at least equal to the 95th percentile of a probability distribution.

Attachment 2.

Gamma Source Modification Factor (GSMF) for Various Ship Types

Table A2-1 of this attachment lists various types of ships and example ship names along with the estimated superstructure ratios and corresponding GSMF. The methods used to estimate GSMF and the key parameters shown in Table A2-1 are described in Weitz (2010).

Table A2-1. Average gamma source modification factors (GSMF) for various ship types

Ship Type	**Designation**	**Example**	L[*] **(m)**	W[*] **(m)**	S_{nom}[*] **(fraction)**	**<*GSMF*> w/o SS**[†]	**<*GSMF*> w/SS**[‡]	
							Average	**95th percentile**
Aircraft Carrier, ASW	CVS	USS BOXER	271	45	0[§]	1.51	1.56	1.60
Aircraft Carrier, Escort	CVE	USS BAIROKO	203	32	0[§]	1.65	1.70	1.74
Amphibious Force Flagship	AGC	USS ESTES	140	19	0.40	1.99	2.95	3.85
Attack Transport	APA	USS GENEVA	139	19	0.50	2.01	3.14	4.31
Battleship	BB	USS NEW YORK	175	29	0.50	1.77	2.58	3.39
Cruiser	CA	USS PENSACOLA	179	20	0.50	1.95	3.07	4.14
Destroyer	DD	USS MANSFIELD	115	12	0.50	2.37	4.06	5.79
Destroyer Escort	DE	USS SILVERSTEIN	93	11	0.50	2.43	4.31	6.25
Dock Landing Ship	LSD	USS BELLE GROVE	140	22	0.40	1.92	2.75	3.56
Fleet Oiler	AO	USS CACAPON	169	23	0.30	1.87	2.57	3.22
Fleet Tug	ATF	USS TAKELMA	62	12	0.35	2.42	3.79	5.09
Infantry Landing Craft	LCI	LCI-327	48	7	0.30	3.03	5.04	7.17
Salvage Ship	ARS	USS BOLSTER	65	12	0.50	2.42	4.20	6.00
Store Ship	AF	USS MERAPI	103	15	0.30	2.18	3.16	4.18
Submarine Rescue Ship	ASR	USS CHANTICLEER	77	13	0.60	2.36	4.40	6.79
Tank Landing Craft	LCT	LCT-1013	36	10	0[**]	2.60	2.80	2.96
Tank Landing Ship	LST	USS LAWRENCE CO.	100	15	0.30	2.19	3.17	4.16

[*] Ship characteristics: L = Length; W = Beam; S_{nom} = Nominal superstructure fraction; SS = superstructure (Weitz, 2010).

[†] This column contains the mean of the distribution of average GSMF values obtained without allowance for superstructure for each ship type.

[‡] These columns contain the average and 95th percentile values of the distribution of average GSMF values calculated for various values of S for each ship type.

[§] As a first approximation, the superstructure of an aircraft carrier was neglected in this assessment because it is located on the extreme starboard side of the flight deck and therefore provides little shielding to those crewmembers who worked on the flight deck.

[**] LCT has a nearly rectangular deck with a modest superstructure at the far aft end.