DEFENSE THREAT REDUCTION AGENCY

NUCLEAR TEST PERSONNEL REVIEW PROGRAM

RADIATION DOSE ASSESSMENT

STANDARD METHOD

UA01 – Dose Uncertainty and Upper-Bound Dose Determinations

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	- Section 5.3.1: Added reference to a case as an example for the treatment of uncertainties for mission film badges. - Minor editorial changes	03/31/2008	Paul K. Blake
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2.0	- Section 5.1.1.1: clarified how the uncertainty factors for neutron dose are applied. - Section 5.1.1.2: clarified that the uncertainty factor of 3 should be applied as a default value for reconstructed external gamma doses. - Section 5.1.2.1: clarified that an uncertainty factor of 1 should be used for doses from incidental ingestion of soil and dust, and doses from inhalation of blast-driven resuspended fallout. - Revised Attachment 1 to improve readability and make corrections. - Updated References, and made editorial changes throughout.	04/30/2021	James D. Franks

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Standard Method

UA01 – Dose Uncertainty and Upper-Bound Dose Determinations

1. Purpose/Summary

This Standard Method (SM) provides the technical and computational methods for assessing the upper-bound doses for external (gamma and neutron), internal, and skin doses for individuals in the Nuclear Test Personnel Review (NTPR) Program according to the procedures specified in SOP RA01. The upper-bound dose represents the estimated dose that was received by less than five percent of the population of participants who were exposed under similar conditions. That is, 95 percent of all the veterans exposed under similar conditions received a dose smaller than the upper-bound dose. As such, the upper-bound dose is the 95th percentile of the dose distribution.

2. Scope

This Standard Method provides technical guidance for calculating the upper-bound external, internal, and skin doses for personnel resulting from exposure to a nuclear detonation and to the resulting radioactive material, including both fallout and activated sources. This Standard Method is used in conjunction with other Standard Methods for assessing radiation exposures 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* (DoD, 2020).

3. Responsibilities

Qualified radiation dose analysis staff members use these methods and associated tools for assessing the upper-bound radiation doses for exposed individuals.

4. Definitions

Uncertainty factor	The ratio of the upper-bound dose to the best estimate dose.
Upper-bound dose	A reconstructed dose that has a 95 percent probability of being higher than the actual dose. This is equivalent to the 95th percentile of a probabilistically determined dose distribution.

5. Method Descriptions

The NTPR Program uses two methods—deterministic and probabilistic—for estimating dose uncertainties with the objective of producing an upper-bound dose that represents at least the 95th percentile of the dose to the exposed population. That is, that the estimated dose in either method will be greater than the dose received by 95 percent of the veterans

in similar conditions. The deterministic method is based on high-sided estimates of key parameters and fixed uncertainty factors that are believed to produce a credible upper bound and are considered "veteran friendly" in the absence of full consideration of uncertainties. The probabilistic method uses Monte Carlo simulations to provide a full analysis of uncertainties. The Monte Carlo simulations consist of randomly sampling values of the input parameters from their credible assigned probability distributions; those values are input to the dose models to build an output distribution of dose, whose summary statistics are calculated. Such distributions account for both inaccuracy, and spatial and temporal variability of input parameters to dose models. Procedures are available (SOP RA01) to select the method that produces a credible upper-bound dose with the best use of time and resources. The following two sections discuss the deterministic and the probabilistic methods.

5.1 Deterministic Method

This section describes the methods used to calculate the upper-bound doses of deterministically reconstructed mean doses and film badge doses. The following subsections discuss the uncertainties and upper-bound doses associated with neutron dose, reconstructed external gamma dose, doses from film badges, reconstructed internal doses, and skin doses.

5.1.1 Uncertainties and Upper Bounds in External Dose

The external doses are treated as if they are normally distributed when combining uncertainties (even if they are more appropriately characterized by a different distribution), and are combined using statistical methods appropriate for normally distributed data. External gamma and neutron doses, if they are accrued from different locations or different sources, are assumed to be statistically independent. Doses from multiple detonations accrued while aboard a given ship or on a particular residence island during a single operation, or during multiple operations where the participant's duties have not appreciably changed, are treated as being correlated, because the major source of uncertainty is from the assumed exposure scenario, e.g., time spent indoors versus outdoors or topside versus below deck. Because neutron doses are reported separately from external gamma doses, the statistical combination of those two doses is unnecessary.

5.1.1.1 Neutron Dose

There are few instances where participants were exposed to neutron radiation from a nuclear detonation. In those cases, rigorous assessments have been performed to determine estimates of the neutron environments created by the respective detonations. As a consequence of adoption of certain recommendations about neutron dose of a committee of the National Research Council of the National Academy of Science (NRC, 2003), earlier best-estimate neutron equivalent doses were increased by approximately a

factor of 2. This increase was mostly due to an increase from 10 to 20 of the radiation weighting factor (previously referred to as "quality factor"). Uncertainties in the original neutron doses were assessed based on estimates of the uncertainties in the underlying parameters (e.g., source spectrum and intensity, flux asymmetry) and combined to generate a total uncertainty in the prompt neutron doses. These methods for estimating uncertainties were reevaluated after NRC's 2003 recommendations and are appropriate for current neutron dose assessments. Thus, to determine upper-bound neutron doses the revised best estimates of neutron doses (Weitz and Egbert, 2010) were multiplied by the neutron dose uncertainty factors derived in the analysis of radiation exposure reports prepared for specific groups and ships for certain operations and shots (commonly called the "White Books," e.g., Goetz et al., 1981). For neutron doses for which uncertainty factors were not previously calculated or are otherwise inadequate, a UF of 3 is recommended by Weitz and Egbert (2010). Reconstructed neutron doses and corresponding upper bounds thus calculated are reported in Weitz and Egbert (2010). Specific information on neutron equivalent doses and their uncertainties is provided for specific operations in SOP Appendices A–C.

5.1.1.2 Reconstructed External Gamma Dose

Upper Bound for Initial Gamma Dose

Whole body external gamma doses from initial gamma radiation are assigned uncertainty factors based on the uncertainties as determined by gamma transport modeling or measurement for participants who were not wearing film badges. The estimates of mean initial gamma dose and the uncertainty factors can be found in the analysis of radiation exposure reports prepared for specific groups and ships for certain operations and shot ("White Books"). Some of the initial gamma doses were found to be underestimated and have been revised (Weitz and Egbert, 2010). To obtain upper-bound initial gamma doses, the available initial gamma uncertainty factors should be multiplied by the revised best estimates for initial gamma doses contained in Weitz and Egbert (2010). For initial gamma doses where an uncertainty factor has not been determined, use the high-sided default uncertainty factor of 3 (Weitz and Egbert, 2010). Specific information on initial gamma doses and their uncertainties is provided for specific operations in SOP Appendices A–C.

Upper Bound for Reconstructed Gamma Dose

Whole body external gamma doses from residual radiation exposure, e.g., fallout, and neutron-activated soil, are assigned a nominal uncertainty factor of 3. Higher factors should be used if demonstrably justified by a greater uncertainty in one or more aspects of the scenario (Schaeffer, 2015).

For a reconstructed deterministic whole body gamma dose, the upper bound is given by:

$$UB_{\gamma} = UF_{ext}\, D_{\gamma} \tag{1}$$

where

UB_γ	=	The upper-bound dose (rem)
D_γ	=	Whole body external gamma dose (rem)
UF_{ext}	=	Uncertainty factor associated with reconstructed whole body external gamma dose

The upper-bound uncertainty factor for whole body external gamma dose is set to 3 in deterministic models as recommended in Schaeffer (2015).

Total Dose, Uncertainty, and Upper Bound for Reconstructed Whole Body External Gamma Dose

For *n* reconstructed deterministic whole body external gamma dose components that are uncorrelated, the total whole body external gamma dose, dose component uncertainty, and the upper-bound dose are given by:

$$D_\gamma = \sum_{i=1}^{n} D_{\gamma,i} \tag{2}$$

$$u_{\gamma,i} = D_{\gamma,i}(UF_{ext} - 1) \tag{3}$$

$$UB_\gamma = D_\gamma + \sqrt{\sum_{i=1}^{n} {u_{\gamma,i}}^2} \tag{4}$$

where

D_γ	=	Whole body external gamma dose (rem)
$D_{\gamma,i}$	=	The i^{th} component of the total gamma dose D_γ (rem)
$u_{\gamma,i}$	=	The uncertainty associated with the i^{th} component of the total reconstructed gamma dose D_γ (rem)
UB_γ	=	The total upper-bound whole body external gamma dose (rem)

5.1.1.3 Dose from Film Badges

Uncertainties associated with film badge readings are treated differently than the uncertainties for reconstructed whole body gamma doses (SM ED01). The uncertainty for film badge readings has many sources and is handled differently for individually issued, permanent or mission, dosimeters than for cohort film badges. Dose uncertainty related to doses from cohort film badges or other dosimeters are addressed at the end of this subsection.

Uncertainties in film badge dosimetry are treated using the guidance contained in the report entitled Film Badge Dosimetry in Atmospheric Nuclear Tests (NRC, 1989). With all dose uncertainty calculations associated with film badges, the total reported mean dose is the officially recorded film badge reading while the upper-bound assessment uses the bias-corrected mean dose, which is derived from recommendations in NRC (1989). The exceptions to this general approach are for Operations BUSTER-JANGLE and TUMBLER-SNAPPER, where the bias correction is greater than the overall uncertainty and the calculated upper-bound dose is less than the reported dose for a given badge. For those operations, the NTPR program considers the recorded film badge reading and the upper bound to be one and the same.

Sources of Uncertainty in Film Badge Readings

The NTPR program implements three of the four principal types of bias and uncertainty that affect film badge dosimetry results for atmospheric nuclear test participants discussed in NRC (1989). These types of bias and uncertainty are radiological, laboratory, and environmental factors. The fourth source of bias and uncertainty discussed in NRC (1989) is the conversion of film badge (FB) exposure in milliroentgens (mR) to Deep-dose Equivalent (DDE) (USNRC, 2020) in millirem (mrem), which is the dose equivalent from penetrating radiation to soft tissue located at a depth of 10 millimeters in the body and is due to variations in geometries and size and shape of individual badge wearers. NTPR does not consider the bias caused by the FB to DDE conversion but does consider the uncertainty (SAIC, 2006).

In addition to the types of uncertainties associated with bias in film badge results, there are several sources of uncertainty due to film badge handling, administration, and documentation. These non-statistical categories of uncertainty include film badge readings incapable of being properly analyzed during processing for the exposure scenario, or due to film badge damage. The handling of these types of uncertainties is discussed in SM ED01.

In addition to the uncertainties associated with individual film badges, the use of cohort film badges creates additional uncertainty. The additional uncertainty is due to variations in activities and locations that would cause variation in the doses between the badge wearing member of the cohort and others in the cohort (NRC, 2003).

Uncertainty and Upper Bound for Film Badge Readings

NTPR uses the FBDOSE program (SAIC, 2006) to estimate the component of external gamma dose, uncertainty, and upper-bound dose from film badge readings. The FBDOSE manual has a detailed discussion of how to run the program, enter data, and use the output. An example of an FBDOSE output (FBDOSE.OUT) is given in Table 1. Although specific to Operation BUSTER-JANGLE, the format in the example in Table 1 is completely generic.

Table 1. Sample Output from FBDOSE Program

		FILM BADGE DOSE EQUIV				
FILM BADGE INTERVAL	MR	MRADJ	LOWER	MEAN	UPPER	UPP90	EXPL CODE
10 28 51 TO 10 28 51	380	380	221	332	498	466	
10 28 51 TO 10 28 51	0	0	0	0	0	0	3
10 30 51 TO 10 31 51	240	240	139	209	314	294	
11 5 51 TO 11 5 51	0	20	0	17	57	47	5
11 19 51 TO 11 19 51	100	100	52	87	145	134	
11 29 51 TO 11 29 51	140	140	77	122	192	178	
11 30 51 TO 12 2 51	320	320	186	279	419	393	
12 3 51 TO 12 3 51	190	190	109	166	252	235	
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TOTALS FOR FB, FBDE:	1370	1390	903	1215	1633	(1557 @ 90 PCT)	

EXPLANATION CODES: 1 = UNIT DOSIMETRY READS ZERO
2 = RECONSTRUCTED ZERO DOSE
3 = NO EXPOSURE POTENTIAL
4 = HELD AS ZERO PENDING RESEARCH TO DEFINE EXPOSURE
5 = CONVERTED TO HALF OF MDL
6 = TOTAL OF MULTIPLE FILM BADGE READINGS

The FBDOSE variable names in the output above are defined as follows:

FILM BADGE INTERVAL – Dates of coverage for each badge as input by the user in MM DD YY format.

MR – Film badge reading (mrem) for each badge and their total sum.

MRADJ –Film badge reading (mrem) adjusted to account for sub-MDL doses and their total sum. In Table 1, the first zero badge was treated as a "definite" zero and the second as a "soft" zero resulting in a dose of 20 mrem, which is half of the minimum detection limit (MDL) of 40 mrem.

LOWER – Lower limit of the 95-percent confidence interval associated with each individual mean dose equivalent and total dose equivalent (mrem). LOWER includes 2.5 percentile of the dose distribution.

MEAN – Central estimate of dose equivalent (mrem) for each exposure and for the total dose equivalent (bias removed).

UPPER – Upper limit of the 95-percent confidence interval associated with each individual mean dose equivalent and total dose equivalent (mrem). UPPER includes 97.5 percentile of the dose distribution.

UPP90 – Upper limit of the 90-percent confidence interval, which brackets the 5^{th} to 95^{th} percentile, associated with each individual mean dose equivalent and total dose equivalent (mrem). This value is used for reporting the 95^{th} percentile upper-bound dose.

In uncertainty calculations, the analyst uses the total in the MRADJ column shown in Table 1 as the total external gamma dose and the total of the UPP90 column as the upper-bound 95th percentile dose. For external dose involving only film badge readings, upper-bound dose and the uncertainty of the film badge dose are given by:

$$D_{\gamma} = FB_{\gamma} \tag{5}$$

$$UB_{FB\gamma} = FB_{UB} \tag{6}$$

$$u_{FB\gamma} = FB_{UB} - FB_{MEAN} \tag{7}$$

where

$FB\gamma$	=	The total dose from all film badge dosimetry taken from the total of the MR column of the FBDOSE output (rem)
$UB_{FB\gamma}$	=	The upper-bound whole body external gamma dose based only on film badges (rem)
FB_{UB}	=	The upper bound for all film badge dosimetry taken from the UPP90 column of the FBDOSE output (rem)
$u_{FB\gamma}$	=	The uncertainty of the film badge gamma dose (rem)
FB_{MEAN}	=	The total mean film badge dose adjusted for bias taken from the MEAN column of the FBDOSE output (rem)

The uncertainty associated with the total film badge dose, $u_{FB\gamma}$, is used to estimate upper-bound doses involving a combination of film badge readings and reconstructed whole body external doses.

Uncertainty and Upper Bound in Cohort Film Badge Readings

Because cohort badges have a greater degree of uncertainty than individually issued permanent or mission film badges, the FBDOSE-based method of uncertainty analysis should not be used (Kocher, 2004). When using cohort film badges, the mean dose should be calculated using the FBDOSE program the same as above. However, when an external gamma dose is estimated based on the results from one or more film badges worn by other members of a participant's exposure cohort, the external uncertainty factor UF_{ext} of 3 for reconstructed doses should be applied instead of UPP90. The uncertainty of the estimated dose should be calculated using Equation 3.

5.1.1.4 Combined Reconstructed and Film Badge External Gamma Doses

The total gamma doses and their associated uncertainties from each of the two categories (reconstructed whole body external gamma and film badge-based) are combined assuming the dose distributions are normal (even though it is likely both tend towards being lognormal or something different entirely). This assumption simplifies the calculations required to generate an upper-bound dose and does not appreciably affect the overall result. As was stated above, what is important to remember is that, if film badges are part of the uncertainty calculation, the reported film badge dose is used for the reported mean total external gamma dose, while the bias-corrected mean dose is used with its associated uncertainty for the upper-bound external gamma dose.

Estimate and Upper Bound for Reconstructed Gamma Dose and Film Badge Dose

For *n* reconstructed gamma dose components and film badge results, the total whole body external gamma dose and the upper-bound dose are given by:

$$D_\gamma = \sum_{i=1}^{n} D_{\gamma,i} + FB_\gamma \tag{8}$$

$$UB_\gamma = \sum_{i=1}^{n} D_{\gamma,i} + FB_{MEAN} + \sqrt{\sum_{i=1}^{n} {u_{\gamma,i}}^2 + {u_{FB\gamma}}^2} \tag{9}$$

Note: the uncertainty for the reconstructed doses is given by Equation 3 and the uncertainty for film badge results is given in Equation 6.

5.1.2 Uncertainties and Upper Bounds in Internal Dose

Prior to NRC's 2003 recommendations, internal doses were reported using a single point estimate that, based on the high-sided value used for the resuspension factor and other factors, was considered to be equivalent to or greater than the 95th percentile. However, the uncertainty in the dose coefficients used to calculate those internal doses was not taken into account. Therefore, it was estimated that all previously reported (upper-bound) internal doses could be low by a factor of 10 or perhaps more. To take these facts into account, an uncertainty factor UF_{int} of 10 was selected (Schaeffer, 2015). Because the previously reported "best estimate" doses were still high-sided, it should be understood that those doses are not true means and that the uncertainty factor of 10 is in addition to the already included high-sided parameters underlying that previously reported best estimate dose. An uncertainty factor of 1 is used for incidental ingestion doses since that internal dose calculation represents an upper-bound estimate (SM ID01).

Internal doses, having uncertainties that are not necessarily related to the source or location of the exposure, may be combined assuming all internal component doses are fully correlated. Though it is possible that there is some degree of independence among the component doses, NTPR assumes the component doses are fully correlated, which high-sides the resultant upper-bound doses. An exception is made when combining internal doses based on mission film badges that have different issue and return dates. This exception is discussed below.

5.1.2.1 Reconstructed Internal Dose

The total and upper-bound doses from intakes by inhalation or ingestion of the combined radionuclides in a mixture produced by alpha particles, or by beta particles plus gamma rays are given by:

$$D = \sum_{i=1}^{n} D_i \tag{10}$$

$$UB = \sum_{i=1}^{n} (UF_{int,i}\ D_i) \tag{11}$$

where

D	=	The total internal dose to a specific organ from all sources of intake (rem)
D_i	=	The i^{th} component of internal dose to a specific organ (rem)
$UF_{int,i}$	=	The uncertainty factor for internal doses to a specific organ is assumed to be 10 in deterministic models, except for incidental ingestion, and inhalation from blast-resuspended fallout, for which the uncertainty factor is assumed to be 1 because the estimated doses are estimates of upper-bound doses (see SM ID01)
UB	=	The upper-bound total internal dose to a specific organ (rem)

5.1.2.2 Additional Uncertainty in Internal Dose from Mission Film Badges with Periods of Coverage Exceeding One Day

When film badge readings from mission film badges are used to determine internal doses, the estimated total dose is determined in accordance with SM ID01. In addition to the internal dose uncertainty described above, an additional uncertainty is added to the overall uncertainty. The additional mission film badge uncertainty is determined using the difference between the internal dose calculated assuming that the entire dose was received on the film badge issue date and the internal dose assuming the entire dose was received on the film badge return date. The mission film badge uncertainty is combined in quadrature such as in Equation 14 with other independent sources of internal dose. The

uncertainty of the internal dose determined from mission film badge results, the uncertainty of internal doses based upon reconstructed gamma doses, and the upper-bound dose for combined internal doses are given by:

$$u_{FB} = D_1 - D_2 \tag{12}$$

$$u_i = D_i(UF_{int,i} - 1) \tag{13}$$

$$UB = D + \sqrt{{u_{FB}}^2 + \sum_{i=1}^{n} {u_i}^2} \tag{14}$$

where

u_{FB}	=	The additional uncertainty for an internal dose calculated using mission film badges that have different issue and return dates (rem)
D_1	=	The internal dose calculated using mission film badge readings assuming all of the dose was received in an 8-hour period on the date of film badge issue (rem)
D_2	=	The internal dose calculated using mission film badge readings assuming all of the dose was received in an 8-hour period on the date of film badge return (rem)
u_i	=	The uncertainty for an internal dose from the i^{th} intake (rem)
UB	=	The upper-bound internal dose of combined internal doses and uncertainties (rem)

5.1.3 Uncertainties and Upper Bounds in Skin Dose

5.1.3.1 Skin Doses from External Sources (Gamma and Beta Shine)

The uncertainties in skin doses from external gamma and beta shine sources not in contact with the skin are generally assumed to be no greater than the uncertainty in the associated external gamma dose from such an external source. This is due, in part, to the fact that the beta-to-gamma ratios used to relate external gamma dose to beta dose were intended to be high-sided estimates. Thus, most beta shine skin doses are assigned the same uncertainty factor (UF_{ext}) as their associated gamma skin dose (Schaeffer, 2015), unless otherwise indicated (Barss and Weitz, 2006). Beta shine doses and their accompanying external gamma skin doses are assumed to be fully correlated, as are most doses from a single source exposure location (e.g., multiple disparate periods aboard the same ship are treated as if all of those individual doses are fully correlated). Skin doses may be calculated from reconstructed external gamma doses or film badges readings.

Total Dose, Uncertainty and Upper Bound for Reconstructed Gamma and Beta Shine Skin Dose

The skin dose for *n* reconstructed external gamma doses is based on the reconstructed gamma doses ($D_{\gamma,i}$). The estimated beta shine skin dose, total skin dose, the uncertainty of the total skin dose, and the upper bound of the total skin dose are given by:

$$D_{\beta,i} = D_{\gamma,i}\ R_{\beta\gamma} \tag{15}$$

$$D_{Skin,i} = (D_{\gamma,i} + D_{\beta,i}) \tag{16}$$

$$D_{Skin} = \sum_{i=1}^{n} D_{Skin,i} \tag{17}$$

$$u_{\beta\gamma,i} = D_{Skin,i}(UF_{ext} - 1) \tag{18}$$

$$UB_{Skin} = D_{Skin} + \sqrt{\sum_{i=1}^{n} u_{\beta\gamma,i}{}^{2}} \tag{19}$$

where

$D_{\gamma,i}$	=	The i^{th} component of the gamma skin dose (rem)
$D_{\beta,i}$	=	The i^{th} correlated corresponding component mean beta skin dose (rem)
$R_{\beta\gamma}$	=	The beta-gamma ratio used to convert reconstructed whole body external gamma doses to beta shine skin doses
$D_{Skin,i}$	=	The i^{th} component of combined beta and gamma skin dose (rem)
D_{Skin}	=	The total skin dose (rem)
$u_{\beta\gamma,i}$	=	The uncertainty associated with the i^{th} component of the beta plus gamma reconstructed skin doses (rem)
UB_{Skin}	=	The total upper-bound skin dose (rem)

Note that it is possible to accrue a gamma skin dose without an accompanying beta shine dose, in which case the corresponding beta terms for that particular gamma dose are all zero.

5.1.3.2 Skin Doses Based on Film Badge Readings

Film badges were often worn in areas affected by fallout or neutron activation and measured the external gamma doses that resulted from exposures to these sources. The beta shine skin dose from accompanying beta radiation, while not directly recorded by

the film badge, can be correlated with the measured gamma dose by means of beta-to-gamma ratios. In such cases, the upper-bound skin dose is calculated based on the upper bound of the film badge dose. The upper bound of a total beta dose that is based on multiple film badge readings can be calculated by multiplying the ratio of the total mean and total upper-bound film badge doses by the total mean beta dose.

Reconstructed Gamma and Beta Skin Dose Combined with Film Badge-Derived Skin Dose

If a skin dose is estimated by reconstructed external gamma doses and film badge doses, the total skin dose and the upper bound of the skin dose are given by:

$$D_{Skin} = \sum_{i=1}^{n} (D_{Skin,i}) + FB_{\gamma}(1 + R_{\beta\gamma}) \tag{20}$$

$$u_{FB\beta\gamma} = (FB_{UB\gamma} - FB_{MEAN})(1 + R_{\beta\gamma}) \tag{21}$$

$$UB_{Skin} = \sum_{i=1}^{n} D_{Skin,i} + FB_{MEAN}(1 + R_{\beta\gamma}) + \sqrt{\sum_{i=1}^{n} u_{\beta\gamma,i}{}^{2} + u_{FB\beta\gamma}{}^{2}} \tag{22}$$

where

$u_{FB\beta\gamma}$ = The uncertainty of the skin dose determined from film badge doses (rem)

The same formula can be used for the combined beta and gamma skin dose that is based only on film badge results by setting the other variables to zero.

5.1.3.3 Skin Contamination Dose

Skin contamination doses were not routinely reported prior to the NRC recommendations of 2003. Thus, a methodology (and accompanying uncertainty analysis) has been developed to address that need (SM ED04). The uncertainties in the doses associated with skin contamination range from a factor of 4 up to a maximum of slightly less than 18 (Schaeffer, 2015), depending on the location of the skin cancer site (Apostoaei and Kocher, 2010). All skin contamination doses can be assumed to be fully correlated. Though it is possible that there is some degree of independence among the component doses, NTPR assumes the component doses are fully correlated.

The total skin contamination dose is simply the sum of all the component skin contamination doses and the total upper-bound skin contamination dose is the sum of all the component upper-bound skin contamination doses. Each component of the skin contamination dose (descending and resuspended) has its own uncertainty. For *n* sources of skin contamination, the total skin contamination dose and the upper-bound skin contamination dose are given by:

$$D_{SC} = \sum_{i=1}^{n} D_{SC,i} \tag{23}$$

$$UB_{SC} = \sum_{i=1}^{n} (UF_{SC,i}\ D_{SC,i}) \tag{24}$$

where

D_{SC}	=	Total skin contamination dose from all sources of contamination (rem)
$D_{SC,i}$	=	The i^{th} component skin contamination dose (rem)
$UF_{SC,i}$	=	Uncertainty factor associated with the i^{th} skin contamination dose
UB_{SC}	=	Upper-bound total skin contamination dose (rem)

5.1.3.4 Combined Skin Dose

The total skin dose is the sum of the component skin doses. As with the external gamma doses, the dose distribution associated with each category of uncertainty is assumed to be normal. The uncertainties would be combined in quadrature and the upper bound would be the sum of the mean doses and the combined uncertainties.

5.2 Probabilistic Method

The alternative approach for treating uncertainties is the probabilistic or Monte Carlo method. In a Monte Carlo simulation, each input parameter is considered as a random variable whose value is determined by randomly sampling from its assigned probability distribution. These distributions reflect the variability and uncertainties in the values of the associated input parameters. The collection of sampled values, one per input parameter, defines a "scenario." An output quantity, such as an external or internal dose, is then computed for each scenario using an algorithm that models the relevant physical and biological processes; this calculation constitutes one "history." By repeating this procedure for many histories, a distribution of output values is accumulated. Analysis of the output distribution yields statistical parameters such as its mean, standard deviation, and percentiles, all of which increasingly represent their corresponding "true" population values as the number of histories increases. Monte Carlo methods can become

computationally intensive if the algorithm is complex and the number of histories is large.

As indicated, the probabilistic method requires that the uncertainties of input parameters be represented as probability distributions. However, not all input parameters require such formal representations. It is obviously unnecessary to develop uncertainty distributions for input parameters that have virtually no uncertainty – an arrival or departure date confirmed by ship's logs, travel orders, flight manifests, morning reports and/or muster logs can be considered to have little or no uncertainty unless there are conflicts in such documentation. (The formal probability distributions in such cases are sharply peaked delta functions). Other input parameters, while uncertain, may have negligible impact on dose and likewise do not require the development of distributions. For example, a participant's arrival date at a test site may be uncertain, but this uncertainty is not important if it is known that he arrived before the first fallout event at a previously uncontaminated location. Thus, the first task in the application of the probabilistic method to dose reconstruction is to screen all input parameters to identify those which warrant the formal development of uncertainty distributions.

The next task is to develop or acquire the requisite parameter uncertainty distributions. Much of the remainder of this section and Attachment 2 are devoted to this topic. Once accomplished, the parameter distributions are input to a computer program which contains the Monte Carlo sampling logic. The program selects values of a parameter from its assigned distribution as it executes the iterative Monte Carlo algorithm to generate the output distributions of external and internal doses. A typical probabilistic dose reconstruction is based on 10,000 histories, each involving the random sampling of multiple input parameter distributions. The 95th percentiles of the output dose distributions, representing the doses accrued by at least 95 percent of the exposed population—personnel involved in similar activities—are taken as the respective upper bounds.

The following two subsections focus on uncertainty modeling of parameters associated with external and internal doses, respectively. The probabilistic methodology has not yet been extended to neutron doses and beta skin/eye doses.

5.2.1 Uncertainties in External Dose

Input parameters for external dose models may be categorized as operational parameters that define a participant's location, movement, and habitat, and environmental parameters that characterize the radiation environment in his vicinity. The modeling of uncertainties for parameters of both types is discussed below.

5.2.1.1 Operational Parameters

Site Arrival/Departure Dates/Times

Dates of arrival and departure from test sites are generally well known. If an uncertainty exists in one of these dates that may impact the reconstructed doses, each of the candidate

dates may be assigned a probability that reflects the likelihood it is the correct date. For arrival date, in light of the remarks made above, this will be required for only if the participant arrived at a previously contaminated location and/or after the first fallout event. As examples, if it is known that a participant arrived at a test site no earlier than May 5 and no later than May 25, in the absence of any other information a uniform distribution covering the inclusive period May 5–25 can be used. If a morning report indicates that he departed on July 25 but travel orders list a departure date of July 28, and the documentation is considered equally authoritative, each of those dates could be assigned a probability of 0.5 and his departure date treated stochastically.

Arrival and departure times are usually less well known than the dates, but they generally have a proportionally smaller impact on reconstructed dose. Time may be important if a radiologically significant event, such as an abrupt, intense period of fallout, occurred on the day of arrival or departure, for which the participant may or may not have been present depending on the timing of his arrival or departure. In cases where the arrival/departure time may be important, that parameter can be modeled as uniform over some interval if all times within that interval are considered equally likely, or with a non-uniform distribution if some times are thought to be more likely than others.

Film Badge Issue/Return Dates/Times

There are frequently inconsistencies in film badge issue and/or return dates entered in the dosimetric record. As a common example, the dosimetry record of a participant issued a sequence of badges states that he turned in his first badge a number of days after receiving his second. If taken literally, this implies that he had two badges in the interim, whereas documented radiation safety procedures indicate that badge turn-in and receipt occurred concurrently. Apparent discrepancies of this type are usually resolved in deterministic assessments by assuming the actual turn-in date of the first badge coincides with the issue date of the second. While this may be a likely scenario, it is still possible that the dates in the dosimetry record are correct. In a probabilistic assessment, the turn-in date can be treated as a random variable to be selected on the basis of probabilities assigned to the two dates.

The time of a film badge exchange is usually unknown. In the unlikely event that this time impacts a dose reconstruction, it can be treated as a random variable in a manner similar to that discussed above regarding arrival and departure times.

Maneuver Characteristics

Maneuvers frequently were conducted at the Nevada Test Site (NTS) in conjunction with nuclear detonations. These events are characterized by parameters such as start times, march rates, distances of closest approach to radioactive objects or sites, and linger times at critical locations. The uncertainties of these and similar continuous parameters can be modeled using probability distribution functions (pdfs) of the forms discussed in Weitz et al. (2009). For example, the uncertainty in rate of march toward an objective can be

represented by a triangular distribution whose defining characteristics (minimum, most likely, and maximum march speeds) are assigned in consideration of the distance, known duration times, weather, and type of terrain traversed. Discrete probability distributions may also be relevant. If it is known that, of 1000 Marines who took part in a maneuver, 700 followed path A to an objective and 300 followed path B, the reasonable pdf for cases where this parameter is unknown would have two discrete outcomes: path A with probability 0.7 and path B with probability 0.3.

Fraction of Time Spent Outside

The fraction of time a participant spent outside versus inside while in a fallout field impacted his external dose because buildings and other structures provide partial shielding to the outside environment. Lacking specific statistical data on this parameter for an individual or a cohort, a triangular distribution is recommended. Factors such as the participant's job, the weather, the availability of outdoor recreational facilities, and veteran-provided information, are considered in assigning the distribution's defining values of minimum, most likely, and maximum fraction of time outdoors. Standard Method ED02 lists default values of the input parameters used in external dose estimations.

Structural Occupancy

The types of structures a participant occupied while not outside impacted his dose because structures of different types provide varying degrees of protection from radiation (see discuss of structural shielding below). It was common for personnel stationed on one of the residence islands in the Pacific Proving Ground (PPG) to work in wood-framed buildings and billet in tents. If, while indoors, a participant spent the majority of his time in one or the other of these two structures, a relevant input parameter is the fraction of his indoor time he spent in a tent (versus in a building). If specific statistical information on this parameter for an individual or cohort is not available, a triangular distribution is recommended. Factors such as job responsibilities, shift hours, and building type are considered in assigning the distribution's defining values of minimum, most likely, and maximum fraction of time inside a tent. ED02 lists default values of the input parameters used in external dose estimations.

5.2.1.2 Environmental Parameters

Film Badge Results

The uncertainty in undamaged film badge exposure readings is modeled by a lognormal distribution (NRC, 1989), which defined two quantities—the measurement bias *B* and the 95^{th} percentile uncertainty factor *K*. As the name implies, *B* is the estimated systematic error or bias introduced into the measurement process by, for example, an error in film calibration, pre-issue exposure to radiation of the film, or fogging of the film due to heat

and/or humidity. The parameter K is a measure of the random error characterized by a lognormal distribution, and is related to the geometric standard deviation (GSD) as follows:

$$K = GSD^{1.645} \tag{25}$$

The usefulness of this parameterization lies in the fact that there is only a 5-percent probability that the true exposure associated with a film badge-measured exposure E—the film badge reading—is greater than $K \cdot E/B$. Estimates of B and K, by nuclear test series, are provided in NRC (1989). From these, the geometric mean $GM = E/B$ and $GSD = K^{1/1.645}$ are determined and the lognormal distribution representing the uncertainty in a film badge reading is thereby defined. The resulting distributions can be combined with the distributions for other dose components to produce an overall dose distribution and associated parameters (mean and upper bound). If a film badge dose is assessed as being from a damaged film badge, then the corresponding dose and uncertainty distribution should be estimated by reconstruction using the methodology provided in Section 5.2.1.1 above (also see SM ED01).

Radiation Intensity Reading Data

The uncertainty in intensity reading data represents the overall error in intensity readings collected using survey meters or similar instruments, then processed and recorded in data logs and other documentation. These errors resulted mainly from inherent instrument precision, calibration error, instrument drift, operator bias, data processing tools, and data recording errors. Based on previous modeling efforts, it is recommended that the uncertainty in intensity reading data be modeled as a normal distribution with an uncertainty factor of 1.5 to 2, as indicated in Table 2. This uncertainty factor, defined as the ratio of the 95th percentile to the mean of the normally distributed intensity reading data, is a dimensionless quantity to be used as a multiplier on the estimated central value of the intensity reading data.

Use of Iso-Intensity Contour Maps

When using measurements or iso-intensity maps to estimate point values in time and space (location), the related uncertainty comprises two components. The first component is the uncertainty from errors in the intensity reading data (see source of uncertainty from radiation intensity reading data discussed above) and uncertainty introduced when maps are created from a discrete and often sparse set of point observation measurement data. The second component is the additional uncertainty that arises when an estimate is made at any point on a map by interpolation (or in some cases by extrapolation) from an iso-intensity contour map. In addition, when assessing the radiation environment for atmospheric nuclear test participants, information on the reliability of data collection and processing is often lacking and adds to the overall uncertainty from modeling the radiation environment.

Table 2. Proposed Ranges of Uncertainty Factors for Estimating Point Values Using Measured Intensities and Iso-Intensity Contour Maps

Source of Uncertainty	Uncertainty Factor *	Distribution	Note
Instrument precision, calibration and operator error (this is applicable when no interpolation is carried out, i.e., where a measurement was recorded at the location of interest)	1.5–2	Normal	Location and time known
With additional uncertainty due to contouring scatter point data	2–3 †	Lognormal/ triangular	Lognormal most adequate for intensity distributions around and not far away from GZ
With additional uncertainty due to using contour maps to determine point estimates by interpolation (factor is higher when location and time of measurements are unknown or inaccurate)	3–5 †	Lognormal/ triangular	Lognormal most adequate for intensity distributions around and not far away from GZ
Additional uncertainty due to using contour maps to determine point estimates by extrapolation	5–10 †	Lognormal/ triangular	Lognormal most adequate for intensity distributions around and not far away from GZ
Extrapolation with high uncertainty from all other sources and surrogate data are used	10–15 ‡	Lognormal/ triangular	Lognormal most adequate for intensity distributions around and not far away from GZ

* The 95-percent uncertainty factor (UF) is the ratio of the 95th percentile to the central estimate of the distribution, which in most cases is the median, mean, or geometric mean (e.g., lognormal distributions).

† Combined uncertainty factors, which include instrument and operator error and all antecedent uncertainty sources.

‡ When surrogate data are used, estimates are presumed to be made by extrapolation, e.g., as when using processed intensity data from a neighboring ship or island.

The guidelines in Table 2 provide ranges of uncertainty factors and types of distributions that are based on the various sources of uncertainties and their cumulative effects (Chehata, 2009). The uncertainty factor, defined as the ratio of the 95th percentile to the central estimate of the variable distribution, is a dimensionless quantity to be used as a multiplier on the estimated central value of the radiation intensity. The selection of an uncertainty factor within the suggested ranges should be based on knowledge of the reliability of the documentation and the methods used to produce the supporting iso-intensity map.

Non-Uniformity of Intensity

A model of the time-dependent, area-averaged outdoor intensity on each of the residence islands at PPG is well established for each fallout event. The outdoor intensity as a function of location on the island undoubtedly varied about this average, and at the locations occupied by a participant (e.g., at his work site, in his billet area, at a recreational area) may have been greater or less than the average. This uncertainty in the site-to-site variation in intensity on the residence islands is characterized with a lognormal distribution having a geometric mean of 1.0 and a geometric standard deviation of 1.5 as provided in SM ED02 and in Weitz et al. (2009).

For ships that received fallout from a nuclear test, the area-averaged topside intensity was frequently documented in deck logs, in operational reports, or an average intensity can reasonably be inferred from intensity readings reported on nearby ships or land masses. The variability of intensity with topside location contributes to the uncertainty in the external dose of an individual crewman who may have manned a topside workstation where the intensity differed significantly from the average. When calculating doses probabilistically the algorithm available in Weitz (2009a) is recommended for estimating the distributions of gamma intensities on the weather decks of fallout-contaminated ships with appropriate user-supplied values of the input parameters to generate ship-specific distributions of topside intensity.

Intensity Decay Rate

The radiation intensity in a fallout contaminated area will decrease with time due to radiological decay and weathering. As discussed in SM ID01 shot-specific, time-dependent radiological decay functions can be obtained directly from the FIIDOS software (Raine et al., 2007). The primary uncertainty in the FIIDOS-derived decay functions is the degree to which radiochemistry data based on cloud samples are representative of the radionuclide mix that was deposited and remained on the ground at any given location. That is, how much fractionation took place during the deposition process and thereafter due to weathering. Inherent in the FIIDOS database is the assumption that no fractionation, other than removal of noble gases, occurred during and after deposition. A rigorous study of fractionation has not yet been performed.

Lacking that, an empirical model of the uncertainty in decay rate was developed and is recommended for NTPR assessments. In that model, the FIIDOS decay functions are multiplied by a time-dependent error factor $(t/t_o)^a$, where exponent a is drawn from an appropriate normal distribution. Justification and details of this model are provided in Weitz et al. (2009). Parameters of the distribution for a are provided in SM ED02.

Structural Shielding

The protection factor *PF* of a land-based structure, such as a building or tent, is defined as the quotient of the free-field radiation intensity outside the structure and the free-field radiation intensity inside the structure. Thus, it is a measure of the radiological protection provided by that structure. When performing probabilistic dose reconstructions for land-based personnel, the uncertainty in *PF* is characterized using both the physical properties of that structure (e.g., its width, length, type of construction material) and on the random location within the structure where an individual can be positioned. The algorithm for developing structure-specific *PF* uncertainty distributions is provided in Weitz (2014) and is recommended as general procedure.

The shielding factor *SF* for ships is defined as the ratio of intensity at some below-deck location to the average topside intensity above the head of the exposed individual. The shielding factor depends on the characteristics of the ship, i.e., maximum width (beam), length, number of decks, deck height, and decking thickness, and on one's position within the ship (which deck and location on that deck). Uncertainties or variability in all these parameters are reflected collectively in the uncertainty distribution of *SF*. The algorithm described in Weitz (2009b) is recommended to calculate ship- and deck-specific shielding factor distributions from contaminants deposited on weather deck surfaces.

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 examination). However, the uncertainty in this parameter is expected to be relatively small and to contribute negligibly to the overall uncertainty in dose. For this reason, uncertainty distributions for F_B have not yet been developed.

5.2.2 Uncertainties in Internal Dose Models

Internal doses from inhalation and ingestion intakes of fallout and of neutron-activated soil and dust are evaluated in probabilistic assessments with the equations given in SM ID01. The input parameters for these internal dose models may be categorized as

environmental parameters that characterize the contaminant environment and biokinetic parameters that relate the contaminant environment to human intake and organ dose. Techniques for quantifying the uncertainties for parameters of both types are discussed below.

5.2.2.1 Contaminant Environment

Activity Fractions of Descending Fallout Particles

Internal dose from inhalation of descending fallout depends on the amount of activity fallout particles contain and the concentration in air of particles that can be inhaled. Particle size and activity are correlated, and as described in Weitz (2009c) these correlations are expressed as activity fractions. An activity fraction is defined as the fraction of total activity that is carried by particles with sizes within a specific range.

For probabilistic dose assessments, the activity fractions AF_1, AF_2, and AF_3 are calculated for the particle aerodynamic diameter in three size classes—1, 2, and 3. These activity fractions are calculated as described in SM ID01 using the parameters AF_{100}, f_1 and f_2, where AF_{100} is the fraction of total activity carried by all particles with diameters less than 100 μm, and f_1 and f_2 are the fractions of AF_{100} that are attributable to particles in size Class 1 and Class 2, respectively.

For a given fallout event, values of the parameters AF_{100}, f_1, and f_2 are randomly sampled from their assigned triangular distributions. A distribution for the fraction of AF_{100} that is attributable to particles in size Class 3 is generated using the quantity $(1 - f_1 - f_2)$. The distribution for AF_{100} is shot-specific, and those for f_1 and f_2 are generic. The minimum, most likely, and maximum values for these uncertainty distributions are provided in Weitz (2009c) and are summarized in SM ID01.

Deposition Velocity

Internal dose from inhalation of descending fallout is inversely related to the velocities at which fallout particles descend to the ground (deposition velocities), as seen in SM ID01. Three such velocities, V_1, V_2, and V_3, one for each of the size classes specified above, have been modeled for use in probabilistic analyses. The uncertainty distributions assigned to these deposition velocities are log-triangular with the parameters given in Weitz (2009c) and in SM ID01.

Gamma Source Modification Factor

Ratios of surface activity density to intensity (Ci m^{-2} per R h^{-1}), generated with the FIIDOS code for infinite plane sources, are used in internal dose calculations to estimate airborne activity concentrations based on intensity measurements. The Gamma Source Modification Factor (*GSMF*) corrects for the fact that the contaminated surface was not infinite in spatial extent, as assumed in the FIIDOS calculations. 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 set equal to 1.

However, for shipboard exposure scenarios, the contaminated area was limited to the weather deck of the ship and the correction is necessary. Weitz (2010) discusses the formulation of *GSMF* for probabilistic assessments of shipboard exposures and provides Mathcad-based programs for generating ship-specific distributions for aircraft carriers, ships with elliptical shapes and superstructure.

Activity Density-to-Intensity (FIIDOS) Ratios

The discussion above on *GSMF* focuses on how to adjust the value of the FIIDOS-generated surface activity density-to-intensity ratios to account for finite source size. There is an underlying uncertainty in the FIIDOS ratios themselves, independent of source size. A major contributor to this uncertainty is fractionation, which has not yet been taken into account. Quantification of this uncertainty is a subject for future study.

Resuspension Factor

The resuspension factor K (m^{-1}), defined as the ratio of air activity concentration in Ci m^{-3} to surface activity density in Ci m^{-2}, is an important input parameter in the calculations of internal dose from resuspended fallout (SM ID01). For a probabilistic analysis, the time-dependent expression given in SM ID01 is used for resuspension due to typical land-based activities. It is recommended that the uncertainty associated with this parameter be estimated for each history by multiplying each calculated value of K by a factor randomly selected from a lognormal distribution with a geometric mean of 1.0 and a geometric standard deviation of 4.05. This distribution, discussed in Weitz et al. (2009) is based on the results of a study reported in Anspaugh et al. (2002).

For blast-driven resuspension of fallout, different resuspension factors are based upon a non-time dependent value of K with a log-normal distribution that depend on proximity to the blast and the size of the blast. The blast-driven resuspension of fallout resuspension factors for the blast-wave region and the thermal-pulse (formerly precursor) region can be found in SM ID01.

5.2.2.2 Biokinetic Parameters

Breathing Rate

Physiological parameters related to ventilation influence the volume and rate of air inhaled and the proportions entering through the nose and mouth, thus affecting the amount of radioactive particles and gases inhaled, their penetration into the respiratory tract, and the quantities deposited.

Breathing characteristics and respiratory parameters vary among individuals because they are largely a function of age and body size, level of physical activity, state of health of

the respiratory tract, and if the individual is a smoker. The distribution of breathing rates appropriate for nuclear test participants developed in Weitz et al. (2009), is recommended for performing probabilistic analyses of internal dose. This distribution is triangular with the defining values of minimum, most likely, and maximum breathing rates given in SM ID01.

Respiratory Tract Deposition Fractions

Respiratory tract deposition fractions are defined as the fractions of inhaled particles in a given size class that deposit in a defined portion of the human respiratory tract. For use in the NTPR probabilistic methodology, deposition fractions for two regions are defined, the posterior extra-thoracic (ET_2) region and thoracic (TH) airway (bronchial, bronchiolar, and alveolar-interstitial regions). Particles are described by the same classes—1, 2, and 3—as those for activity fractions. Characterizations of deposition fractions of particle size classes for use as modifying factors are described in SM ID01 and are designated in Mathcad implementations as R_1, R_2, and R_3 for particles that deposit in the thoracic region, and as NR_1, NR_2, and NR_3 for particles that deposit in ET_2. These characterizations are derived in McKenzie-Carter and Stiver (2009). The values and distributions of these modifying factors, are provided in SM ID01. These multiplicative parameters are used only in descending fallout scenarios (SM ID01).

Dose Conversion Factors

Dose conversion factors (*DCF*s) are used in NTPR dose reconstructions for the assessment of doses accrued from internally deposited radionuclides by the inhalation and ingestion pathways. Specific applications to the reconstruction of internal doses resulting from the inhalation of resuspended and descending fallout are given in SM ID01.

The uncertainties in inhalation and ingestion *DCF*s are incorporated into the NTPR modeling by multiplying the unbiased *DCF*s—discussed in SM ID01—by lognormal distributions. For these lognormal distributions, the geometric means are set equal to 1.0 and the geometric standard deviations are assigned such that the ratios of the 95^{th} percentiles to their geometric means are 30 (equivalent to $GSD = 7.91$) for alpha *DCF*s and 10 ($GSD = 4.05$) for beta-plus-gamma *DCF*s (Weitz et al.; 2009; Kocher et al., 2009). These parameters are also provided in SM ID01.

Incidental Ingestion

A pathway considered in the case studies of land-based units is incidental ingestion, a chronic type of exposure that involves the daily intake of relatively small quantities of contaminated soil and dust. The sources of the ingested contamination include direct contact with airborne soil and dust due to walking, vehicular traffic, and wind-driven lofting of contaminated particles in areas where military personnel were temporarily

stationed. Routine daily activities by test participants may also have involved the inadvertent ingestion of small quantities of soil and dust particles that adhered to food, beverages, cigarettes, or their hands.

SM ID01 contains the equation describing the basis for probabilistic assessments of internal dose from incidental ingestion. Uncertainty models for most of the parameters appearing in that equation (e.g., intensity, DCF_{ing}) have been addressed in Weitz et al. (2009). There are two parameters specific to this pathway, however, whose uncertainties are additionally modeled. These parameters are q_{ing}, the soil ingestion rate, and ρ_{soil}, the bulk density of the soil. It is recommended that the uncertainties of both these quantities be modeled with triangular distributions, the characteristics of which are developed in Chehata and Stiver (2009) and tabulated in SM ID01.

5.2.3 Treatment of Correlations

Potential correlations among uncertainties of key parameters must be considered in formulating the Monte Carlo sampling of parameter values from their assigned pdfs. The degree of correlation between two parameters can range continuously from none (their values are completely independent) to full (the value of one is entirely predictable based on the value of the other). Nevertheless, correlations between parameters in NTPR probabilistic assessments have been assumed to be either non-existent or full; methods of modeling partial correlations have not yet been integrated into the probabilistic formalism. Correlations are addressed much more fully in Appendix G of Weitz et al. (2009).

In performing probabilistic analyses of internal dose accrual, it is recommended that uncertainty distributions that are uncorrelated be sampled independently by drawing separate random numbers during each history. It is further recommended that fully correlated distributions be sampled using the same random number.

6. Data and Input

Operation and shot-specific data are compiled in SOP Appendices A–C. Attachment 1 to this standard method provides sample uncertainty calculations. Attachment 2 provides guidance on the implementation of the pdfs described in Weitz et al. (2009) used in probabilistic dose calculations.

7. Referenced SOPs from this Manual

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

(2) SM ED01 - Film Badge Dose Assessment

(3) SM ED02 - Whole Body External Dose Assessment

(4) SM ID01 - Doses to Organs from Intake of Radioactive Materials

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Attachment 1 Sample Uncertainty Calculations

The following sections contain calculations and clarifying explanations detailing how to calculate the total upper-bound doses in various situations. All equations cited are described in Section 5.1.

A1-1 Sample Calculations for External Gamma Doses

a. Independent Reconstructed Gamma Doses

This example is for two reconstructed external gamma doses: a reconstructed dose $D_{\gamma,1}$ of 1.0 rem and a reconstructed dose $D_{\gamma,2}$ of 0.1 rem. Using Equation 2, the total reconstructed external gamma dose is:

$$D_\gamma = D_{\gamma,1} + D_{\gamma,2} = (1.0 \text{ rem} + 0.1 \text{ rem}) = 1.1 \text{ rem}.$$

Using Equation 3 above, the uncertainty for $D_{\gamma,1}$ is:

$$u_{\gamma,1} = D_{\gamma,1} \times (UF_{ext} - 1) = 1.0 \text{ rem} \times (3 - 1) = 2 \text{ rem}$$

and the uncertainty for $D_{\gamma,2}$ is:

$$u_{\gamma,2} = D_{\gamma,2} \times (UF_{ext} - 1) = 0.1 \text{ rem} \times (3 - 1) = 0.2 \text{ rem}.$$

Using Equation 4, the upper bound for the total estimated gamma dose is then:

$$UB_\gamma = D_\gamma + (u_{\gamma,1}{}^2 + u_{\gamma,2}{}^2)^{1/2} = (1.1 \text{ rem}) + (2.01 \text{ rem}) = 3.11.$$

b. A Reconstructed Gamma Dose and a Film Badge Dose

This example is for a reconstructed external gamma dose ($D_{\gamma,1}$) of 1.0 rem and a film badge dose (FB_γ) using the data from the FBDOSE output in Table 1 (Section 5.1.1.3). Using Equation 8, the total estimated whole body external gamma dose (D_γ) is:

$$D_\gamma = D_{\gamma,1} + FB_\gamma = (1.0 \text{ rem} + 1.370 \text{ rem}) = 2.370 \text{ rem}$$

where FB_γ is the total from the MR column in the FBDOSE output.

The uncertainty for $D_{\gamma,1}$ ($u_{\gamma,1}$) is:

$$u_{\gamma,1} = D_{\gamma,1} \times (UF_{ext} - 1) = 1.0 \text{ rem} \times (3 - 1) = 2.0 \text{ rem}.$$

Using Equation 7, the uncertainty of the film badge dose FB_γ ($u_{FB\gamma}$) is:

$$u_{FB\gamma} = FB_{UB} - FB_{MEAN} = (1.557 \text{ rem} - 1.215 \text{ rem}) = 0.342 \text{ rem}.$$

This quantity is the total of the UPP90 column from the FBDOSE output minus the total of the MEAN column of the FBDOSE output.

Using Equation 9, the upper bound for the total reported gamma dose is:

$$D_{\gamma,1} + FB_{MEAN} + (u_{\gamma,1}{}^2 + u_{FB\gamma}{}^2)^{1/2} = 1.0 \text{ rem} + 1.215 \text{ rem} + [(2.0 \text{ rem})^2 + (0.342 \text{ rem})^2]^{1/2}$$

$$= (2.215 \text{ rem} + 2.029 \text{ rem}) = 4.24 \text{ rem}.$$

A1-2 Sample Calculation for Total Internal Dose

This example is for two internal doses to the same organ: a reconstructed beta-gamma dose from inhalation of resuspended fallout (D_1) of 1.0 rem and an incidental ingestion dose D_2 of 0.1 rem. Note that the method does not change with additional internal doses, there are just more terms.

Using Equation 10, the total internal dose (D) is:

$$D = D_1 + D_2 = (1.0 \text{ rem} + 0.1 \text{ rem}) = 1.1 \text{ rem}.$$

Using Equation 11, the upper bound for the internal dose for a single organ is:

$$UB = (UF_{int,1} \times D_1 + UF_{int,2} \times D_2) = (10 \times 1 \text{ rem} + 1 \times 0.1 \text{ rem}) = 10.1 \text{ rem}.$$

A1-3 Sample Calculation for Total Skin Contamination Dose

This example is for two independent skin contamination doses: a dose $D_{SC,1}$ of 2.0 rem and a dose $D_{SC,2}$ of 0.2 rem. The uncertainty factors $UF_{SC,1}$ and $UF_{SC,2}$ are assumed to be the same for both doses and are 11 for this example. The uncertainty factors are determined as part of the original skin contamination dose. The value of 11 represents the midpoint of the range of 4–18 for the uncertainty factor applied to dermal contamination (Schaeffer, 2015).

Using Equation 22, the total skin contamination dose (D_{sc}) is:

$$D_{sc} = D_{SC,1} + D_{SC,2} = (2.0 \text{ rem} + 0.2 \text{ rem}) = 2.2 \text{ rem}.$$

Using Equation 23, the upper-bound dose (UB_{SC}) is:

$$UB_{SC} = (D_{SC,1} \times UF_{SC,1}) + (D_{SC,2} \times UF_{SC,2}) = (2.0 \text{ rem} \times 11) + (0.2 \text{ rem} \times 11) = 24.2 \text{ rem}.$$

A1-4 Sample Calculation for Total Skin Dose from External Sources

a. Independent Reconstructed Gamma and Beta Shine Doses

This example is for two reconstructed external gamma skin doses and two beta skin doses that are correlated with the external gamma skin doses. One reconstructed gamma skin dose ($D_{\gamma,1}$) is 0.3 rem and the second reconstructed gamma dose ($D_{\gamma,2}$) is 0.1 rem. Assuming a beta-gamma ratio ($R_{\beta\gamma}$) of 7.3 (ED03), the correlated beta skin doses are:

$$D_{\beta,1} = D_{\gamma,1} \times R_{\beta\gamma} = (0.3 \text{ rem} \times 7.3) = 2.2 \text{ rem}$$

$$D_{\beta,2} = D_{\gamma,2} \times R_{\beta\gamma} = (0.1 \text{ rem} \times 7.3) = 0.73 \text{ rem}$$

Using Equation 16, the total gamma and beta shine skin dose is:

$$D_{skin} = D_{\gamma,1} + D_{\beta,1} + D_{\gamma,2} + D_{\beta,2} = (0.3 \text{ rem} + 2.2 \text{ rem} + 0.1 \text{ rem} + 0.73 \text{ rem}) = 3.33 \text{ rem}.$$

Using Equation 18, the uncertainty for $D_{Skin,1}$ ($u_{\beta\gamma,1}$) is:

$$u_{\beta\gamma,1} = (D_{\gamma,1} + D_{\beta,1}) \times (UF_{ext} - 1) = (0.3 \text{ rem} + 2.2 \text{ rem}) \times (3 - 1) = 5.0 \text{ rem}.$$

and the uncertainty for $D_{Skin,2}$ ($u_{\beta\gamma,2}$) is:

$$u_{\beta\gamma,2} = (D_{\gamma,2} + D_{\beta,2}) \times (UF_{ext} - 1) = (0.1 \text{ rem} + 0.73 \text{ rem}) \times (3 - 1) = 1.66 \text{ rem}$$

and using Equation 19, the upper-bound dose is:

$$UB_{skin} = D_{skin} + [(u_{\beta\gamma,1})^2 + (u_{\beta\gamma,2})^2]^{1/2} = 3.33 \text{ rem} + [(5.0 \text{ rem})^2 + (1.66 \text{ rem})^2]^{1/2}$$
$$= (3.33 \text{ rem} + 5.27 \text{ rem}) = 8.6 \text{ rem}$$

b. A Reconstructed Gamma and Beta Dose and a Film Badge Dosimeter with a Corresponding Beta Dose

This example is for a simplified total skin dose using a reconstructed whole body external gamma dose ($D_{\gamma,1}$) of 0.3 rem and the sample FBDOSE output in Table 1. Assuming a beta-gamma ratio ($R_{\beta\gamma}$) of 7.3, the correlated beta skin dose ($D_{\beta,1}$) is:

$$D_{\beta,1} = D_{\gamma,1} \times R_{\beta\gamma} = (0.3 \text{ rem} \times 7.3) = 2.2 \text{ rem}$$

The total skin dose from the reconstructed skin dose is:

$$D_{skin,1} = D_{\gamma,1} + D_{\beta,1} = (0.3 \text{ rem} + 2.2 \text{ rem}) = 2.5 \text{ rem}$$

The uncertainty of the total reconstructed skin dose $D_{skin,1}$ ($u_{\beta\gamma,1}$) is:

$$u_{\beta\gamma,1} = (D_{\gamma,1} + D_{\beta,1}) \times (UF_{ext} - 1) = (2.5 \text{ rem}) \times (3 - 1) = 5.0 \text{ rem}$$

For the film badge dose, from Table 1 (Section 5.1.1.3):

FB_{γ} is 1.370 rem (the total of the MR column of the FBDOSE output)

FB_{MEAN} is 1.215 rem (the total of the MEAN column of the FBDOSE output)

$FB_{UB\gamma}$ is 1.557 rem (the total of the UPP90 column of the FBDOSE output).

Using Equation 20, the total reported skin dose from gamma and beta dose from both the reconstructed external gamma dose and the film badge dose is:

$$D_{skin,1} + FB_{\gamma} \times (1 + R_{\beta\gamma}) = 2.5 \text{ rem} + [1.370 \text{ rem} \times (1 + 7.3)] = 13.9 \text{ rem}$$

Using Equation 21, the uncertainty of the total skin dose determined from film badge doses $u_{FB\beta\gamma}$ is:

$$u_{FB\beta\gamma} = (FB_{UB\gamma} - FB_{MEAN}) \times (1 + R_{\beta\gamma}) = (1.557 \text{ rem} - 1.215 \text{ rem}) \times (1 + 7.3) = 2.85 \text{ rem}$$

Using Equation 22, the upper bound for the total skin dose is:

$$UB_{skin} = D_{skin,1} + FB_{MEAN} \times (1 + R_{\beta\gamma}) + [(u_{\beta\gamma,1})^2 + (u_{FB\beta\gamma})^2]^{1/2}$$
$$= 2.5 \text{ rem} + 1.215 \text{ rem} \times (1 + 7.3) + 5.75 \text{ rem} = 18.4 \text{ rem}$$

Attachment 2 Implementation of Probability Density Functions in Mathcad

Mathcad is the software platform most likely to be used for probabilistic dose reconstructions in the NTPR Program. For that reason, the implementation in Mathcad of specific and arbitrary probability density functions is outlined in this attachment.

Mathcad has a rather large array of pdfs in its internal library, including uniform, Gaussian, and lognormal. Hence, sampling from these pdfs can be readily implemented using the following standard Mathcad commands.

- R_i = runif(n,a,b)$_i$ – produces n values of a random variable R uniformly distributed between a and b.
- R_i = rnorm(n,μ,σ)$_i$ – produces n values of a random variable R normally distributed with mean μ and standard deviation σ.
- R_i = rlnorm(n,ln(GM),ln(GSD))$_i$ – produces n values of a random variable R lognormally distributed with geometric mean GM and geometric standard deviation GSD.

There is a straightforward way of sampling from a pdf that is not in the Mathcad library, such as the triangular distribution. Let x be the variable of interest (e.g., a time duration, intensity reading, shielding factor) and $P(x)$ the pdf that characterizes the uncertainty in x. The cumulative probability function $C(x)$ is defined as:

$$C(x) = \int_{-\infty}^{x} P(x')dx' \qquad \text{(A2-1)}$$

The following algorithm allows one to sample x from an arbitrary pdf $P(x)$:

1. Perform the integration indicated in Equation A2-1, either in closed form or numerically, and set the resulting expression equal to a constant R, i.e., $C(x) = R$.
2. Solve this expression for x as a function of R, giving $x = f(R)$.
3. Sample R from a uniform random distribution between 0 and 1. This sampling can be accomplished using the Mathcad command for uniform distribution given above.
4. The resulting $x_i = f(R_i)$ will be distributed according to $P(x)$.

As an example of the use of this algorithm when $P(x)$ is expressed in a functional form that allows closed-form integration of Equation A2-1, consider a triangular distribution defined by $P(a) = 0$, $P(m) = P_k$ (peak value), and $P(b) = 0$, where $a \le m \le b$. The constraint that $C(\infty) = 1$ requires that $P_k = 2/(b\text{-}a)$. (Alternatively, this can be derived

without formally integrating $C(x)$ by noting that the total area under $P(x)$ is $\frac{1}{2}\cdot P_k\cdot(b\text{-}a)$. $P(x)$ can then be written in functional form as:

$$P(x)=\begin{cases}\dfrac{2(x-a)}{(m-a)(b-a)} & for\ a\le x\le m\\ \dfrac{2(b-x)}{(b-m)(b-a)} & for\ m<x\le b\end{cases} \tag{A2-2}$$

Substituting Equation A2-2 into Equation A2-1 and integrating gives:

$$C(x)=\begin{cases}\dfrac{(x-a)^2}{(m-a)(b-a)} & for\ a\le x\le m\\ \dfrac{m-a}{b-a}+\dfrac{(x-m)}{(b-m)(b-a)}(2b-m-x) & for\ m<x\le b\end{cases} \tag{A2-3}$$

Setting each of the two components of $C(x)$ in Equation A2-3 equal to R and solving the quadratic equations for x yields the desired result:

$$x=\begin{cases}a+\sqrt{R(m-a)(b-a)} & for\ 0\le R\le (m-a)/(b-a)\\ b-\sqrt{(1-R)(b-m)(b-a)} & for\ (m-a)/(b-a)<R\le 1\end{cases} \tag{A2-4}$$