DEFENSE THREAT REDUCTION AGENCY

NUCLEAR TEST PERSONNEL REVIEW PROGRAM

RADIATION DOSE ASSESSMENT

STANDARD METHOD

ED04 – Skin Dose from Dermal Contamination

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
1.2	- No Rev. 1.1 of this SM was produced. - New version. Revision 1.0 (considered a working draft) was completely rewritten to produce Rev. 1.2.	10/31/2008	Paul K. Blake
1.3	-Added references -Minor editorial changes	01/31/2010	Paul K. Blake
2.0	- In Section 5.2, added SDMF values for several additional skin sites - In Section 5.2, updated the SDMF values for consistency with Apostoaei and Kocher (2010) - In Section 5.3.2, updated the values and list of skin sites for the Interception and Retention Fraction (*R*). - Section 5.3.1, revised definition and equation for *FR*(t) to be consistent with SM ID01 - Updated reference list - Other editorial changes	04/30/2021	James D. Franks

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Standard Method

ED04 – Skin Dose from Dermal Contamination

1. Purpose/Summary

Standard Method (SM) ED04, *Skin Dose from Dermal Contamination*, provides general technical methods for assessing dose from radioactive contaminants deposited on skin or clothing of individuals in the Nuclear Test Personnel Review (NTPR) Program according to the procedures specified in SOP RA01.

2. Scope

This standard method provides technical guidance for reconstructing skin doses due to beta and gamma radiation emitted from contaminants deposited on the skin or clothing. This standard method should not be used to determine skin doses due to alpha radiation or internally deposited radionuclides, nor should it be used as the sole method for determining skin exposures when the methods of SM ED03 - *Skin Dose from External Sources* also apply. This standard method is used in conjunction with other standard methods for assessing whole body 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 radiation doses for exposed individuals. It is the responsibility of the 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 appropriate staff personnel so that the methodology can be extended as required to provide adequate estimates of skin doses from dermal contamination. 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

Activity concentration or activity density:

- On a surface — Radioactivity per unit surface area (typically in units of curies per meter squared, abbreviated as Ci m^{-2}).
- In air — Radioactivity per unit volume of air (typically in units of Ci m^{-3}).

Dermal Contamination	Radioactive material deposited on the skin.
Individual	Any person (member of the Armed Forces or civilian) who participated in the nuclear weapons testing program.
Mixed Fission Products	The aggregate of radioactive nuclei that results from the fissioning of fissile material (e.g., U-235 and Pu-239) in a nuclear detonation.
NTS	Nevada Test Site.
Particle Size Distribution	The distribution of sizes in a collection of particles, such as those which comprise fallout deposited at a specific range from and time after a nuclear detonation. Such particles are classified as follows (Apostoaei and Kocher, 2010):
− Small particles	Collection of particles with diameters less than 100 micrometers (µm) and median diameter less than 50 µm.
− Large particles	Collection of particles with a large fraction of particle diameters greater than 50 µm and median diameter 100 µm or greater.
− Intermediate particles	Collection of particles with a size distribution intermediate between those for small and large particles, having a median diameter between 50 and 100 µm.
PPG	Pacific Proving Ground, renamed Enewetak Proving Ground in 1958.
Specific activity	Radioactivity per unit mass (e.g., in curies per gram, or Ci g^{-1}).

5. Method Description

Skin doses from dermal contamination resulted from depositions of mixed fission products on skin and clothing from descending and resuspended fallout, and from contact with contaminated surfaces. The specific skin dose pathways addressed in this standard method are:

- Deposition of descending fallout on skin and clothing
- Deposition of resuspended fallout on skin and clothing
- Direct transfer of contaminants from surface to skin
- Indirect transfer of contaminants from surface to skin (i.e., transfer from surface to hand, followed by transfer from hand to skin site).

Notice that skin doses from fallout deposited in the environment, e.g., “shine” from ground-deposited fallout and other contaminated surfaces, are discussed in SM ED03.

5.1 General Approach for Skin Contamination

The dose (rad) at depth x in the skin, accrued during the time interval t_1 to t_2 (hours) from radionuclides deposited on the skin, is given by:

$$D(x) = \int_{t_{start}}^{t_{end}} C_{skin}(t) \cdot DCF_{skin}(x,t) \cdot dt \tag{1}$$

where

$C_{skin}(t)$	=	Activity concentration on the skin surface (Ci m^{-2}) at time t (h)
$DCF_{skin}(x,t)$	=	Skin dose conversion factor for x and t (rad h^{-1} Ci^{-1} m^{2}) (See Table 1 for values
t_{start}	=	Time after detonation of the onset of dermal contamination (h)
t_{end}	=	Time after detonation that the dermal contamination is removed (h)

If the activity on the skin surface was mixed fission products produced in a nuclear detonation, all times are measured relative to the time of the detonation.

For most dermal contamination scenarios, $DCF_{skin}(x,t)$ is only weakly dependent on time over the duration of exposure. In such cases, the dependence on time can be suppressed and Equation 1 simplifies to:

$$D(x) = DCF_{skin}(x) \int_{t_{start}}^{t_{end}} C_{skin}(t)\ dt \tag{2}$$

The skin dose conversion factor, which is independent of the deposition mechanism, is discussed in the following section. The activity concentration on the skin, which is dependent on the deposition mechanism, is addressed for each pathway in subsequent sections.

5.2 Skin Dose Conversion Factor

Radiation transport techniques were employed to calculate $DCF_{skin}(x,t)$ for dermal contact with mixed fission products from a nuclear detonation. Beta and gamma emission spectra for fast fission of U-235, taken from Finn et al. (1979), were used to define the source terms in the one-dimensional electron-photon transport code CEPXS (Lorence et al., 1989). Skin is assumed to have the composition and density (1.09 g cm^{-3}) specified in Woodard and White (1986). The values of $DCF_{skin}(x,t)$ thus derived are provided in Table 1 in units of rad h^{-1} Ci^{-1} m^{2} for time t ranging from 1 hour to 2 years after detonation and for depth x up to 400 μm. Self-shielding of the skin-deposited particles has been neglected in this analysis.

Table 1. Skin Dose Conversion Factor $DCF_{skin}(x,t)$ (rad h^{-1} Ci^{-1} m^2)

Time t	Depth x (μm)										
(hours)	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	**400**
1	1280	1130	1040	970	910	860	830	790	760	730	410
2	1290	1130	1030	960	910	860	820	790	760	730	400
4	1290	1130	1030	960	900	850	810	780	750	720	390
6	1300	1130	1030	960	900	850	810	780	750	720	380
12	1300	1130	1030	950	890	840	800	770	740	710	370
24	1330	1140	1020	940	870	820	780	740	710	680	320
48	1350	1140	1010	920	850	800	750	710	670	640	270
72	1370	1140	1000	910	840	780	730	690	650	620	240
168	1380	1140	990	890	820	750	700	660	620	590	190
336	1380	1140	990	890	820	750	700	660	620	590	190
720	1380	1140	1000	900	820	760	710	660	630	590	210
1440	1380	1140	990	890	810	750	700	660	620	580	200
2880	1380	1130	990	880	810	740	690	640	600	570	190
4320	1380	1130	990	880	810	740	690	640	610	570	190
6480	1370	1130	990	890	810	750	700	650	610	580	210
8640	1360	1130	990	890	820	760	710	660	630	590	220
17280	1350	1130	1000	900	830	770	720	680	640	610	240

The basal cell layer between the epidermis and the dermis is considered the target organ for stochastic effects such as skin cancer. The depth of the radiosensitive basal cells varies with anatomical location, ranging from 20 to 100 μm over much of the body (ICRU, 1997). The average depth of the basal cell layers of the face, forehead, neck, shoulders, torso, and upper legs is 40 μm, while the average depth in the forearms and lower legs is 80 μm. The largest thickness of the epidermis is found on the palms of the hands and soles of the feet. These regions also exhibit the largest variation in thickness from area to area. While the "horny pads" of the palms and soles can be as much as 600 μm thick, in other areas the thickness can be as low as 200 μm. A thickness of 400 μm is generally accepted as an average for these sites (Apostoaei and Kocher, 2010).

An expedient approach often used in dermal contact dose reconstruction is to ignore the time dependence of the skin dose conversion factor over the period of exposure, thus allowing the use of Equation 2, and to express $DCF_{skin}(x)$ with the equation:

$$DCF_{skin}(x) = 900 \cdot SDMF(x) \tag{3}$$

where

SDMF	=	Skin dose modification factor (See below for values)
900	=	Nominal value of skin dose conversion factor DCF_{skin} (rad h^{-1} Ci^{-1} m^2) (Barss, 2000)

The "skin dose modification factor" $SDMF(x)$ adjusts the nominal value of 900 rad h^{-1} Ci^{-1} m^2 according to the depth of the basal cell layer at the target skin site. Based on the data in Table 1, specific skin site values of *SDMF* have been estimated and are shown in Table 2.

Table 2. Recommended Values for SDMF

Skin Site	SDMF
Face, behind ears*, forehead, neck, shoulders, chest*, torso, under belt*, and upper legs	1.3
Back of neck*, forearms, lower legs, and under boot edge*	0.9
Scalp*, palms of hands, backs of hands*, and soles of feet	0.3

* SDMF values for these skin sites are not available in Apostoaei and Kocher (2010). The indicated values are recommended based on similar skin thickness or proximity to other sites on the body.

5.3 Skin Dose from Descending Fallout

Unsheltered personnel (i.e., those outdoors on land and topside on a ship) during periods of fallout deposition were exposed to an accumulation of contaminants on their skin. The activity concentration (in Ci m^{-2}) on a land surface or weather deck of a ship during a fallout event is represented by a time-dependent function $C_{surf}(t)$, where t is the time after detonation. For an unsheltered individual, some fraction F_{des} of the descending activity (designated the "effective interception and retention fraction") was intercepted by and retained on his skin. Thus, the activity concentration on his skin can be expressed by the equation:

$$C_{skin}(t) = C_{surf}(t) \cdot F_{des} \tag{4}$$

where

$C_{surf}(t)$	=	Surface activity concentration (Ci m^{-2})
F_{des}	=	Effective interception and retention fraction

Methods for estimating $C_{surf}(t)$ and F_{des} are presented in the following sections.

5.3.1 Surface Activity Concentration – $C_{surf}(t)$

The surface activity concentration at the location occupied by the individual during the deposition period is estimated from the measured or reconstructed intensity *I*(*t*) in that vicinity. This is accomplished through the use of time-dependent ratios of the intensity (R h^{-1}) above an infinite, planar surface to the activity density (Ci m^{-2}) of mixed fission products on that surface. Designated here as *FR*(*t*) , these shot-specific ratios were generated with the FIIDOS code (Raine et al., 2007) and are available in Appendix H of this SOP Manual. In this formulation, the surface activity density is given by:

$$C_{surf}(t) = GSMF \cdot FR(t) \cdot I(t) \tag{5}$$

where

GSMF	=	Gamma source modification factor
FR(*t*)	=	Time-dependent, shot-specific surface activity–intensity ratio (“FIIDOS Ratio”) for an infinite plane estimated using FIIDOS; historically called $\frac{SA}{I}(t)$ (Ci m^{-2} per R h^{-1})
I(t)	=	Intensity (R h^{-1})

The factor *GSMF* (gamma source modification factor) corrects for the fact that the contaminated surface was not infinite in spatial extent, as assumed in the FIIDOS calculations that generated *FR*(*t*). 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. Average values of *GSMF* for various types of ships are given in SM ID01.

5.3.2 Effective Interception and Retention Fraction – F_{des}

Apostoaei and Kocher (2010) developed a method of estimating the accumulation of radioactive particles on the skin of an unsheltered individual exposed to descending fallout. The method is based on a study of the interception and retention of particles of volcanic ash on the skin of humans in the aftermath of eruptions of the Irazu Volcano in Costa Rica in 1965 and 1966. The measured interception and retention fractions deduced from that study are modified by a number of adjustment factors to account for differences between the conditions under which that experiment was conducted and the conditions appropriate for descending fallout scenarios. Thus, F_{des} can be expressed as the product of four factors with the equation:

$$F_{des} = R \cdot PS \cdot EM \cdot EF \tag{6}$$

where

R	=	Measured interception and retention fraction
PS	=	Particle size factor
EM	=	Moisture factor
EF	=	Enrichment factor

The *R* is the ratio of the mass per unit (skin) area deposited on skin to the mass per unit (ground) area deposited on the ground surface, as determined from the set of volcanic ash measurements.

The *PS* is an adjustment factor which accounts for the dependence of retention probability on particle size for material impacting the skin, and the difference between the particle size distribution at a fallout location of interest and the volcanic ash particle size distribution for which R was measured.

The *EM* is an adjustment factor that accounts for increased retention efficiency due to moisture on skin and/or particles.

The *EF* is an adjustment factor that accounts for the difference between the specific activity (Ci g^{-1}) of fallout particles retained on skin and the specific activity of fallout particles on the ground.

The brief discussions of these factors in subsequent subsections are largely summaries of more detailed presentations given by Apostoaei and Kocher (2010).

5.3.2.1 Measured Interception and Retention Fraction – *R*

The values of *R*, as determined from the volcanic ash data, are generally less than unity since the skin on most areas of the body cannot retain a mass of descending contaminant per unit area larger than that found on the ground surface. *R* may exceed 1; however, for special regions of the body (designated as “build-up barriers”) where descending contaminants may be collected and retained. Examples of build-up barriers include the back of the neck under the collar, under the belt, under a boot edge, and behind the ears.

The values of *R* used for skin dose reconstruction are provided in Table 3. In addition to the best estimates (deterministic values) of *R* for the various body regions, the table also provides the corresponding 95th percentile upper bounds. For body locations not listed in Table 3, the parameters for the scalp are used as defaults.

Table 3. Interception and Retention Fraction (*R*)

Skin Site	Deterministic Value*	95th Percentile Upper Bound*
Face, neck†, shoulders, back and sides of torso, forehead, palms of hands, and soles of feet†	0.015	0.12
Chest (unspecified amount of hair)	0.03	0.28
Forearms, backs of hands†, upper legs, and lower legs (above boot edge)	0.06	0.36
Scalp	0.23	1.0
Back of neck under collar, under belt, under boot edge, and behind ears	1.5	5.0

* Interception and retention fractions and upper bounds were taken from Apostoaei and Kocher (2010).

† Interception and retention fractions for these skin sites are not available in Apostoaei and Kocher (2010). The indicated values are recommended based on similarity to other sites.

5.3.2.2 Particle Size Factor – *PS*

The likelihood that an intercepted particle is retained on the skin depends primarily on the particle's size. Particles with diameters less than about 50 µm have nearly equal probabilities of retention, while those with diameters greater than 50 µm have retention probabilities which are inversely proportional to particle diameter. Thus, the interception and retention fractions must be adjusted to account for the fact that the particle size distributions of the descending fallout to which individuals were exposed differed from the size distribution of volcanic ash for which the data was taken.

It was observed in the volcanic ash study that 30–40 percent of the total ash mass consisted of particles with diameters less than 50 µm (Apostoaei and Kocher, 2010, Figure 4-1). If the fraction of mass composed of particles with diameters less than 50 µm in a specific instance of descending fallout is known to have been f_{des}, an estimate of the *PS* factor is obtained by simply taking the ratio of the two fractions using the equation:

$$PS = f_{des} / 0.3 \qquad (7)$$

Most often, however, size distribution data for specific fallout events are not available, In this case, the distribution must be characterized from less direct information. Figure 1 (taken from Glasstone and Dolan, 1977) is useful in estimating the size of particles that reached the ground at a given time after detonation (abscissa) from a given altitude (ordinate). Applying this to a fallout event, the relevant time is the time after detonation that fallout occurred at the location of interest, and the relevant altitude is the stabilized height of the bottom of the radioactive cloud. This height is about 30,000 feet for a typical nuclear detonation; more specific values are available for many shots in Hawthorne (1979). Note that particle size is given as radius in this graph.

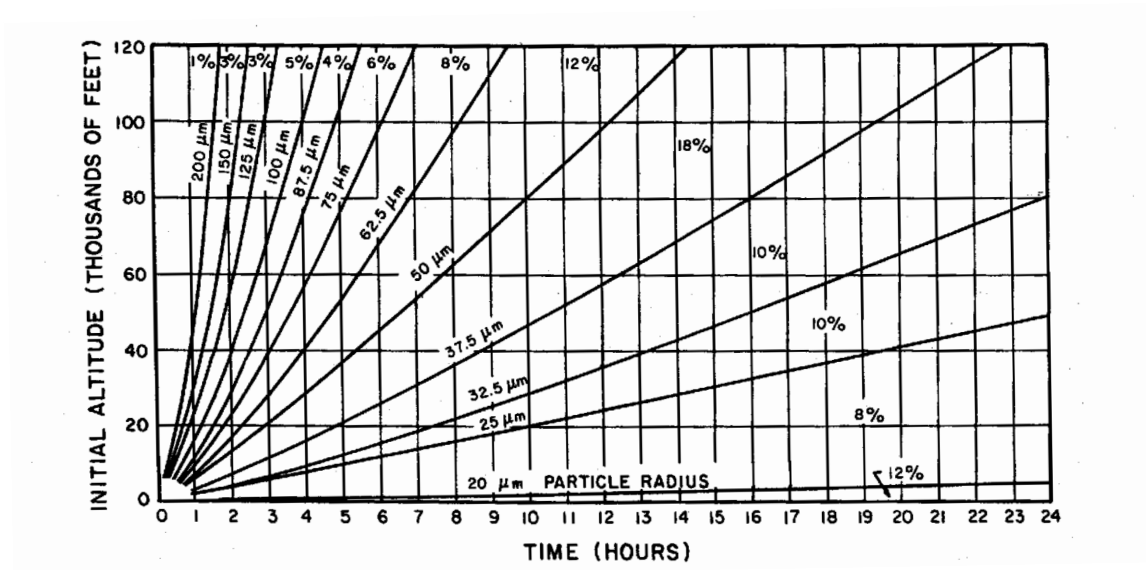

Figure 1. Fall Times of Particles of Different Sizes from Various Altitudes

(Also shown is the typical percentage of activity in each particle size class)

As an example, consider fallout from Operation GREENHOUSE, SHOT DOG at Enewetak Island. The fallout started about 2 hours after detonation and the intensity peaked about 3 hours later before subsiding (Thomas et al., 1979). The bottom of the cloud stabilized at 33,000 feet within minutes after detonation (Hawthorne, 1979). From Figure 1 (for time = 5 hours and altitude = 33 kft), the particles that contributed to this fallout event mostly had diameters of 2 × 47 µm = 94 µm or greater. This is consistent with the observation in Cooney, 1951 regarding the size of these fallout particles and characterizes this as large particle fallout, as defined in Section 4. Again referring to Figure 1, most particles with diameters of 50 µm or less would not have reached the ground until at least 16 hours after the detonation.

Fallout on the residence islands of Enewetak Atoll during Operation HARDTACK I was dominated by the combined depositions from Shots FIR and KOA about 2 days after the Shot FIR detonation and 1 day following Shot KOA. It is evident from Figure 1 that this fallout consisted predominantly of small particles and therefore is characterized as small particle fallout, per Section 4.

As a general rule of thumb, in the absence of more specific particle size information,

- For fallout composed of small particles, use PS = 1.3 and a 95th percentile upper bound of 1.6.

- For fallout composed of large particles, use *PS* = 0.8 and a 95th percentile upper bound of 1.0.
- For fallout composed of intermediate particles, use *PS* = 1.0 and a 95th percentile upper bound of 1.5.

Note: The small, large, and intermediate particle classes are defined in Section 4.

5.3.2.3 Moisture Factor – *EM*

Retention of particles on the skin is enhanced if the skin and/or the incident particles are moist. The volcanic ash data were collected in the mild, humid climate of Costa Rica.

Participants of testing at the Pacific Proving Ground (PPG) operated in a warm climate that was as humid as, and at times more humid than, that of Costa Rica. Therefore, the mean and 95th percentile upper bound of *EM* used for PPG exposures are 1.2 and 1.5, respectively. The climate at the Nevada Test Site (NTS) in the early morning when most of the testing took place was cool and dry. Consistent with this, the mean and 95th percentile upper bound of *EM* used for NTS exposures are 0.75 and 1.0, respectively.

5.3.2.4 Enrichment Factor – *EF*

Studies indicate that the specific activity (i.e., activity per unit mass) of fallout particles on skin can be greater than the specific activity of fallout particles on the ground. An “enrichment factor” is defined as the ratio of these specific activities. This effect can be understood as follows. If radionuclides were distributed uniformly throughout the volumes of all particles, the specific activity would be independent of particle size and no enrichment would take place. In the process of particle formation after a nuclear detonation, however, fractionation of radionuclides occurs: some radionuclides (mainly those of refractory elements such as zirconium, niobium, and cerium) tend to be volumetrically distributed in larger particles while others (mainly those of volatile elements such as cesium, strontium, and iodine) tend to be distributed on the surfaces of smaller particles. The specific activities of the smaller, surface-coated particles are generally greater than those of the larger particles. As discussed previously, the probability of particle retention on the skin is also greater for smaller than larger particles. This correlation between specific activity and retention probability produces the enrichment effect.

Fallout at locations relatively close to ground zero (e.g., those within the boundaries of the NTS) consisted of large particles, as defined in Section 4. Most of these particles contained predominantly refractory elements that were volumetrically distributed, which by themselves would have produced no enrichment. However, volatile radionuclides coalesced on the surfaces of the smaller particles in the fallout distribution, and this small-particle component created the potential for significant enrichment. For exposure to large-particle descending fallout, the mean and 95th percentile upper bound of *EF* are set to 2.5 and 3.5, respectively.

At locations far from ground zero (e.g., most residence sites at PPG), fallout consisted of small particles that had a higher proportion of volatile radionuclides deposited on their surfaces and relatively high specific activities. Nevertheless, it is expected that only a modest amount of enrichment occurred there because most of the radionuclides were entrained in small particles, and these particles were retained on skin with roughly the same efficiency. Therefore, the mean and 95th percentile upper bound of *EF* used for small particle fallout are 1.3 and 1.8, respectively.

For exposure to descending fallout composed of intermediate particles, the mean and 95th percentile upper bound of *EF* are taken as 2.0 and 3.7, respectively.

5.3.3 Skin Dose Calculations for Descending Fallout

A composite expression for calculating the skin dose accrued during the time interval t_1 to t_2 from dermal contact with descending fallout is obtained by combining Equation 1 with Equations 4 through 6 and gives the equation:

$$D_{des}(x) = R \cdot PS \cdot EM \cdot EF \cdot GSMF \cdot \int_{t_1}^{t_2} I(t) \cdot \frac{SA}{I}(t) \cdot DCF_{skin}(x,t)\, dt \qquad (8)$$

where

$D_{des}(x)$ = Absorbed dose to skin at depth x from descending fallout (rad)

All factors in this equation are defined and discussed above. Values of $DCF_{skin}(x,t)$ from Table 1 can be used in Equation 8, or the approximate methods of Equations 2 and 3 can be employed to move this factor outside the integral. Intensity $I(t)$ is formulated on the basis of measurements or reconstruction. The shot-specific functions $FR(t)$ are available in SOP Appendix H. *GSMF* is addressed in Section 5.3.1. The factors *R*, *PS*, *EM*, and *EF*, the product of which is the effective interception and retention fraction F_{des}, are discussed and quantified in subsections 5.3.2.1–5.3.2.5, respectively; means and 95th percentile upper bounds of these parameters are summarized in Table 3 and Table 4.

Table 4. Summary of Factors in the Calculation of F_{des}

Parameter	Deterministic Value	95th Percentile Upper Bound
R: Interception and Retention Fraction	See Table 2	See Table 2
PS: Particle Size Factor*		
Small particles	1.3	1.6
Large particles	0.8	1.0
Intermediate particles	1.0	1.5
EM: Moisture Factor		
Pacific Proving Ground	1.2	1.5
Nevada Test Site	0.8	1.0
EF: Enrichment Factor		
Small particles	1.3	1.8
Large particles	2.5	3.5
Intermediate particles	2.0	3.7

*Operation-specific values should be used when available.

5.4 Skin Dose from Resuspended Fallout

Dermal contamination resulted not only from descending fresh fallout, but also from previously deposited fallout that was resuspended in the air and subsequently deposited on the skin. Resuspension occurs as a natural phenomenon (i.e., wind-driven resuspension) and as a result of human activities (e.g., pedestrian and vehicular traffic, helicopters operations). An individual who worked or resided in a region where fallout had been previously deposited (referred to as a "fallout field") is assumed to have been exposed to resuspended fallout for the duration of time he spent outside (or topside), Even after his exposure to resuspended fallout ended when he relocated to an uncontaminated area (e.g., by going inside or below deck), the radioactive contaminants that had accumulated on his skin remained there until later removed, usually by washing. The analysis of skin dose from these exposures is more involved than that which led to Equation 8 for descending fallout, and is addressed in an NTPR technical memorandum (Weitz, 2011). Initial steps in this analysis include determination of the airborne activity concentration ($C_{air}(t)$) and the development of an effective interception and retention factor F_{res} for the resuspension scenario.

5.4.1 Airborne Activity Concentration $C_{air}(t)$

For large areas that are relatively uniformly contaminated, the airborne activity concentration within a few meters of the contaminated surface can be related to the surface activity concentration with the equation:

$$C_{air}(t) = C_{surf}(t) \cdot K(t') \tag{9}$$

where

$C_{air}(t)$	=	Concentration in air (Ci m^{-3})
$K(t)$	=	Resuspension factor (m^{-1})
t	=	Time after detonation (h)
t'	=	Time after end of fallout (h)

In most cases, the radiation intensity peaked at the end of fallout deposition, so t' is usually referenced to the time of the peak intensity. If Δt is the time interval (hours) from detonation to peak intensity at the location of interest, then $t' = t - \Delta t$.

After a fallout episode, the fraction of material deposited on the ground surface that is available for resuspension decreases with time due to downward migration of fallout particles and other fallout-soil attachment processes. The following equation (USNRC, 1983) models this effect and provides the basis to calculate time-dependent resuspension factors for land-based long-term exposures of personnel at the PPG or NTS with the equation:

$$K(t') = 10^{-5} \times e^{-0.01 \times \frac{t'}{24}} + 10^{-9} \quad \mathrm{m}^{-1} \tag{10}$$

In addition, values of K for specific short duration activities, such as troop maneuvers involving helicopter operations in contaminated areas, aircraft decontamination, trucking, digging trenches, etc., are provided in Table A3-1 in SM ID01.

The flux of airborne contaminants is given by the equation:

$$\phi_{air}(t) = V \cdot C_{air}(t) \tag{11}$$

where

$\phi_{air}(t)$	=	Flux of airborne activity (Ci m^{-2} s^{-1})
V	=	Average velocity of resuspended contaminants (see below) (m s^{-1})

In this expression, V is assumed to be the wind speed if the movement of contaminants was primarily induced by the wind. On the basis of meteorological data, wind speeds of 5 m s^{-1} and 4 m s^{-1} are normally assumed for PPG and NTS, respectively. For an individual walking in a contaminated area on an essentially windless day, where the resuspension is driven primarily by mechanical disturbance (i.e., the action of walking), an average deposition velocity of 1 m s^{-1} applies. Deposition velocities can reach 7 to 14 m s^{-1} if exposure occurs while riding in the back of a truck moving at 15 to 30 mile per hour (Apostoaei and Kocher, 2010). The uncertainties in these velocities are included in the 95^{th} percentile upper bound of the collection efficiency (*CE*) reported in Table 5.

5.4.2 Effective Retention Fraction – F_{res}

If an airborne activity flux $\phi_{air}(t)$ is incident on bare skin, the amount of activity per unit area intercepted by the skin during an incremental time interval from t to $t + dt$ is $\phi_{air}(t) \cdot dt$ (Ci m^{-2}). Only a fraction F_{res} ("effective retention fraction") of this activity will stick to the skin. Thus, the incremental amount of contamination $dC_{skin}(t)$ retained on the skin during this interval is given by the equation:

$$dC_{skin}(t) = 3600 \cdot F_{res} \cdot \varphi_{air}(t) \cdot dt = 3600 \cdot F_{res} \cdot V \cdot GSMF \cdot I(t) \cdot \frac{SA}{I}(t) \cdot K(t') \cdot dt \qquad (12)$$

where

F_{res} = Effective retention fraction

Equations 5, 9, and 11 have been utilized to obtain the second expression. The factor 3600 converts from hours to seconds.

Borrowing from the development in Section 5.3.2 of an analogous parameter for the retention of descending fallout, F_{res} is expressed as the product of five factors:

$$F_{res} = CE \cdot \frac{R}{R_{fa}} \cdot PS \cdot EM \cdot EF \qquad (13)$$

where

CE	=	Collection efficiency
R/R_{fa}	=	The ratio of R, the interception and retention fraction for the skin site of interest to the fraction (R_{fa}) determined from those studies for the bare forearm
PS	=	Particle size fraction
EM	=	Moisture factor
EF	=	Enrichment factor

The *CE* fraction is the fraction of particles incident on bare skin that are retained on the skin, as determined by wind tunnel studies. The largest value reported for this parameter (Asset and Pury, 1954) is 0.02, based on an experiment in which wind-driven small particles (almost all less than 50 μm in diameter) were incident on a bare forearm. This value is taken as both the mean and the 95th percentile upper bound for *CE*. This approach differs from that of Apostoaei and Kocher (2010), who apply the volcanic ash data to resuspended fallout as well as to descending fallout.

The R/R_{fa} ratio was derived from the volcanic ash studies with values for R given in Table 3 and an estimated R_{fa} value of 0.06. This ratio allows the collection efficiency to be estimated for body sites other than the forearm.

The *PS* fraction is the fraction of resuspended fallout particles that have diameters less than 50 μm, divided by the fraction of particles used in the referenced wind tunnel experiment that had diameters less than 50 μm. The latter fraction is very nearly one. The size distribution of resuspended particles has not been studied, but it is certain to be dependent on the magnitude of the disturbance causing the resuspension. If that disturbance is light wind, the particle size distribution will consist mostly of small particles (those with diameters less than 50 um), so $PS \approx 1$. If the disturbance is strong (e.g., strong wind or mechanical disturbance such as vehicular traffic), the lofted particulates will contain some intermediate and even large particles, making *PS* less than 1. In the limiting case of a very strong disturbance (e.g., blast wave or helicopter takeoff/landing), the size distribution of resuspended particles may even approach that of the deposited fallout. Given the uncertainty associated with this parameter, the high-sided assumption is made that $PS = 1$.

The *EM* factor is an adjustment factor that accounts for an increase in collection efficiency due to moisture on skin and/or particles. The mean of *EM* is taken as 3.0 with a 95th percentile upper bound of 3.9 for resuspension in PPG because the wind tunnel data were collected under dry conditions. The mean and 95th percentile upper bound used for NTS exposures are 1.0 and 1.3, respectively

The *EF* factor is an adjustment factor that accounts for the difference between the specific activity (Ci g^{-1}) of fallout particles retained on skin and the specific activity of resuspended particles. *EF* for resuspended material is assumed to have a mean value of 1.0 and a 95th percentile upper bound of 1.3.

5.4.3 Skin Dose Calculations for Resuspended Fallout

Consider the scenario of an individual exposed to resuspended fallout from a time t_{start} to a later time t_{end}, during which contaminants were continuously deposited on his bare skin. The accumulated contaminants then remained on his skin from t_{end} until they were removed by washing at t_{wash}. All times are in hours after detonation. It is shown in Weitz (2011) that, on the basis of Equations 1 and 12, the following expression for the dose at depth x in the skin from contact with resuspended fallout is obtained.

$$D_{res}(x) = 3600 \cdot V \cdot F_{res} \cdot GSMF \cdot \left\{ \int_{t_{start}}^{t_{end}} K(\tau - \Delta t) \cdot \left[\int_{\tau}^{t_{wash}} FR(t) \cdot I(t) \cdot DCF_{skin}(x,t) \cdot dt \right] d\tau \right\} \qquad (14)$$

where

t_{wash} = time after shot that contamination was removed by washing (h)

Values of $DCF_{skin}(x,t)$ from Table 1 can be used in Equation 14, or the approximate methods of Equations 2 and 3 can be employed to move this factor outside the integrals. Intensity $I(t)$ is formulated on the basis of measurements or reconstruction; the shot-specific functions $FR(t)$ are available in SOP Appendix H; and *GSMF* is addressed in Section 5.3.1. Estimates of $K(t)$ and V are provided in Section 5.3.1. The factors comprising F_{res} are discussed and quantified in subsections 5.4.2; means and 95th percentile upper bounds of these parameters are summarized in Table 5. Values for t_{start}, t_{end}, and t_{wash} are selected on the basis of the type and schedule of work performed by the individual.

Table 5. Summary of Factors in the Calculation of F_{res}

Parameter	Deterministic Value	95th Percentile Upper Bound
CE: Collection Efficiency	0.02	0.06
R/R$_{fa}$: Ratio of Interception and Retention Fractions for Descending Fallout	See Table 3	See Table 3; upper bound of *R* for forearms, backs of hands, and upper/lower leg is set equal to 0.06, i.e., no error for resuspension
PS: Particle Size Factor	1.0	1.0
EM: Moisture Factor		
Pacific Proving Ground	3.0	3.9
Nevada Test Site	1.0	1.3
EF: Enrichment Factor	1.0	1.3

In many scenarios of interest, the time-dependent functions $I(t)$, $K(t')$, $FR(t)$, and $DCF(x,t)$ vary negligibly during the time interval $t_{start} \rightarrow t_{wash}$. In this case, these functions can be replaced by their average values over that time interval in the equation:

$$D_{res}(x) \approx 3600 \cdot V \cdot F_{res} \cdot GSMF \cdot \overline{G} \cdot \overline{I} \cdot \overline{K} \cdot \overline{DCF(x)} \cdot [½ \cdot (\Delta t_{res})^2 + \Delta t_{res} \cdot \Delta t_{wash}] \qquad (15)$$

where

$\overline{I}$,	=	Average intensity (R h^{-1})
$\overline{K}$,	=	Average resuspension factor (m^{-1})
$\overline{G}$	=	Average ratio of surface activity to intensity. (Ci m^{-2} R^{-1})
$\overline{DCF(x)}$	=	Average skin dose conversion factor (rad Ci^{-1})
Δt_{res}	=	The duration spent in the fallout field ($t_{end} - t_{start}$) (h)
Δt_{wash}	=	The time interval from exiting the fallout field to removing the deposited contaminants from the skin by washing ($t_{wash} - t_{end}$) (h).

Equations 14 and 15 represent single-day exposures to resuspended fallout. Often an individual resided and/or worked for an extended period in a fallout field, and consequently was exposed repeatedly to resuspended fallout. On a ship, these exposures were limited to 4 days after the end of shipboard deposition in the present model, since the resuspension factor is assumed to have been zero after that time. On land, the cycle was repeated daily until personnel permanently departed from the test site. These scenarios are accommodated by applying Equation 14 or 15 to each day's exposure and summing the daily skin doses.

5.5 Skin Dose Calculations from Prior Detonations

Dermal contamination due to resuspension of previously deposited ("old") fallout by the thermal pulse or blast wave produced in a detonation at NTS (an acute event) can be estimated by assuming that a fraction of the activity on the ground is resuspended and then redeposited in roughly the same area. Thus, skin dose due to exposure to resuspended old fallout by a thermal pulse or blast wave is calculated in a manner analogous to that due to descending fallout (Apostoaei and Kocher, 2010). The dose produced by old fallout is given by:

$$D_{old}(t_{old}, x) = [f_R \cdot f_D \cdot C_{surf}(t_{old})] \cdot F_{des} \cdot DCF(x, t_{old}) \cdot \Delta t \qquad (16)$$

where

$D_{old}(t_{old},, x)$	=	Dose from old fallout (rad)
t_{old}	=	Time after the detonation (h)

In this equation, the surface activity density of old fallout $C_{surf}(t)$ is evaluated with Equation 5, the effective interception and retention fraction F_{des} with Equation 6, and the skin dose conversion factor *DCF(x,t)* with Table 1 or Equation 3; Δt is the duration of exposure (h).

The (unitless) parameter f_R represents the fraction of activity on the ground that is resuspended and remains in the air at the time deposition on the skin occurs. The resuspension factor, f_R, can be estimated as follows:

$$f_R = K \cdot H \tag{17}$$

where

f_R	=	Resuspension fraction
K	=	Resuspension factor (m^{-1})
H	=	Height of a layer of air were radionuclides are uniformly distributed (m)

For personnel such as forward observers who were impacted by dust resuspended by a blast wave at the time of detonation, a reasonable mean value of K is 10^{-4} m^{-1}, with a 95th percentile upper bound of 10^{-3} m^{-1}. Typically, H is on the order of 100-300 m (Barrett et al., 1986).

In addition, f_D is a (unitless) dispersion factor that accounts for the fact that the activity resuspended by a nuclear detonation can be spread over a larger area around ground zero than it originally occupied. When a dispersion factor applies, it is estimated by assuming a blast wave resuspended material from a circle with a radius R_1 and dispersed it over a circle with a larger radius R_2. If the initial concentration of material on the ground was uniform and the resuspended material is assumed to have been dispersed uniformly by the blast wave, the dispersion factor is given by the ratio of the areas of the two circles. Therefore, if R_2 is twice R_1, the dispersion factor is $(R_1/R_2)^2 = 0.25$.

In considering exposure to radionuclides in old fallout resuspended by a detonation, it is important to distinguish between (1) individuals designated as forward observers and located in the blast-wave region at the time of detonation and (2) individuals (e.g., maneuver troops) entering the blast-wave or precursor region at some time after a detonation. The important difference is that forward observers were exposed to resuspended fallout particles of all sizes, whereas individuals who entered the blast-wave or precursor region after a detonation were exposed only to small resuspended particles, because larger particles (i.e., particles with diameters greater than about 100 µm) were redeposit quickly and were not present in the air at the time of exposure. Another important difference is that forward observers were exposed in a very short period of time (acute exposure), while maneuver troops generally spent a longer period of time (up to hours) in lingering clouds in the blast-wave or precursor region. Therefore, Equation 16 is used to assess doses for forward observers from exposures to particles resuspended by the blast wave. Doses for maneuvering troops are calculated using the equations in Section 5.4.

6. Data and Input

Operation and shot-specific data are compiled 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 ED03 - Skin Dose from External Sources

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

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