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# Derivation of Effective Resuspension Factors in Scenarios for Inhalation Exposure Involving Resuspension of Previously Deposited Fallout by Nuclear Detonations at Nevada Test Site

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This report presents an evaluation of inhalation doses in scenarios for exposure of military participants at atmospheric nuclear-weapons tests at the Nevada Test Site that involved unusually high resuspension of radionuclides in previously deposited fallout by the thermal pulse or blast (shock) wave produced in an above-ground detonation. The purpose of this evaluation was to determine values of a resuspension factor, defined as the ratio of the concentration of resuspended radionuclides in air above ground to the areal concentration on the ground surface, that should be assumed in those scenarios to ensure that point estimates of inhalation dose obtained in dose reconstruction would be credible upper bounds, i.e., at least upper 95% credibility limits.

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# CONVERSION TABLE

Conversion Factors for U.S. Customary to metric (SI) units of measurement.

| MULTIPLY → / TO GET ← | BY | TO GET → / DIVIDE ← |
|---|---|---|
| angstrom | 1.000 000 x E -10 | meters (m) |
| atmosphere (normal) | 1.013 25 x E +2 | kilo pascal (kPa) |
| bar | 1.000 000 x E +2 | kilo pascal (kPa) |
| barn | 1.000 000 x E -28 | meter$^2$ ($m^2$) |
| British thermal unit (thermochemical) | 1.054 350 x E +3 | joule (J) |
| calorie (thermochemical) | 4.184 000 | joule (J) |
| cal (thermochemical/$cm^2$) | 4.184 000 x E -2 | mega joule/$m^2$ (MJ/$m^2$) |
| curie | 3.700 000 x E +1 | *giga bacquerel (GBq) |
| degree (angle) | 1.745 329 x E -2 | radian (rad) |
| degree Fahrenheit | $t_k = (t°f + 459.67)/1.8$ | degree kelvin (K) |
| electron volt | 1.602 19 x E -19 | joule (J) |
| erg | 1.000 000 x E -7 | joule (J) |
| erg/second | 1.000 000 x E -7 | watt (W) |
| foot | 3.048 000 x E -1 | meter (m) |
| foot-pound-force | 1.355 818 | joule (J) |
| gallon (U.S. liquid) | 3.785 412 x E -3 | meter$^3$ ($m^3$) |
| inch | 2.540 000 x E -2 | meter (m) |
| jerk | 1.000 000 x E +9 | joule (J) |
| joule/kilogram (J/kg) radiation absorbed dose | 1.000 000 | Gray (Gy) |
| kilotons | 4.183 | terajoules |
| kip (1000 lbf) | 4.448 222 x E +3 | newton (N) |
| kip/inch$^2$ (ksi) | 6.894 757 x E +3 | kilo pascal (kPa) |
| ktap | 1.000 000 x E +2 | newton-second/$m^2$ (N-s/$m^2$) |
| micron | 1.000 000 x E -6 | meter (m) |
| mil | 2.540 000 x E -5 | meter (m) |
| mile (international) | 1.609 344 x E +3 | meter (m) |
| ounce | 2.834 952 x E -2 | kilogram (kg) |
| pound-force (lbs avoirdupois) | 4.448 222 | newton (N) |
| pound-force inch | 1.129 848 x E -1 | newton-meter (N-m) |
| pound-force/inch | 1.751 268 x E +2 | newton/meter (N/m) |
| pound-force/foot$^2$ | 4.788 026 x E -2 | kilo pascal (kPa) |
| pound-force/inch$^2$ (psi) | 6.894 757 | kilo pascal (kPa) |
| pound-mass (lbm avoirdupois) | 4.535 924 x E -1 | kilogram (kg) |
| pound-mass-foot$^2$ (moment of inertia) | 4.214 011 x E -2 | kilogram-meter$^2$ (kg-$m^2$) |
| pound-mass/foot$^3$ | 1.601 846 x E +1 | kilogram-meter$^3$ (kg/$m^3$) |
| rad (radiation dose absorbed) | 1.000 000 x E -2 | **Gray (Gy) |
| roentgen | 2.579 760 x E -4 | coulomb/kilogram (C/kg) |
| shake | 1.000 000 x E -8 | second (s) |
| slug | 1.459 390 x E +1 | kilogram (kg) |
| torr (mm Hg, $0^0$ C) | 1.333 22 x E -1 | kilo pascal (kPa) |

*The becquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.
**The gray (Gy) is the SI unit of absorbed dose.

## ABSTRACT

This report is concerned with inhalation doses in scenarios for exposure of military participants at atmospheric nuclear-weapons tests at the Nevada Test Site that involved high resuspension of previously deposited fallout by an above-ground detonation. The purpose is to derive values of a resuspension factor, defined as the ratio of the concentration of resuspended radionuclides in air above ground to the areal concentration on the ground surface, that should be assumed in those scenarios to ensure that point estimates of inhalation dose that are obtained in dose reconstructions would be credible upper bounds, i.e., at least upper 95% credibility limits, when point values of all other parameters that are normally used in estimating inhalation doses in any resuspension scenario are assumed. The other parameters include the areal concentrations of radionuclides in previously deposited fallout, the breathing rate, and dose coefficients for inhalation, which give equivalent doses to specific organs or tissues per unit activity of radionuclides inhaled. The desired resuspension factors, which are called "effective" resuspension factors, are derived on the basis of an analysis of uncertainty in the model currently used to estimate inhalation doses in any resuspension scenario that takes into account subjective estimates of uncertainty in all parameters, including the resuspension factor. Results of the uncertainty analysis indicate that effective resuspension factors for all radionuclides in previously deposited fallout that should be assumed to ensure that point estimates of equivalent dose to any organ or tissue are credible upper bounds when the usual point values of other parameters are assumed are $10^{-3}$ $m^{-1}$ in the region closest to ground zero where the thermal pulse that was produced in a detonation was an important cause of resuspension and $10^{-4}$ $m^{-1}$ in the region farther from ground zero where resuspension was caused only by the blast wave. These effective resuspension factors were determined mainly by the assumed uncertainties in dose coefficients for inhalation of radionuclides, resuspension factors that apply to all fallout on the ground surface, and the inhalable fraction of resuspended radionuclides. The extent of the thermal-pulse and blast-wave regions and the time periods after a detonation over which effective resuspension factors should be applied in those regions are discussed.

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# 1. INTRODUCTION

This report presents an assessment of certain scenarios for inhalation exposure of military participants in the atmospheric nuclear-weapons testing program at the Nevada Test Site (NTS) that involved unusually high resuspension of previously deposited fallout by above-ground detonations.[1] The purpose of this assessment is to derive values of a resuspension factor, defined as the ratio of the concentration of resuspended radionuclides in air above ground to the areal concentration on the ground surface, that should be assumed in reconstructing inhalation doses in those scenarios when standard methods of inhalation dose reconstruction for military participants that were developed by the Defense Threat Reduction Agency (DTRA) are used.

Resuspension of previously deposited fallout by a nuclear detonation is a potential concern at NTS whenever participants were located within a few miles of ground zero at times shortly after detonation and fallout from one or more previous shots had been deposited at those locations. Such exposure scenarios occurred only at certain above-ground detonations at NTS, beginning with Shot FOX in Operation TUMBLER-SNAPPER in 1952; they did not occur at surface or underground shots at times earlier in the period of atmospheric testing at NTS, because there was no previously deposited fallout in areas where resuspension by a detonation could have occurred or participants were not located in those areas at times shortly after a detonation (Dancz and Chehata, 2006).[2]

The potential importance of inhalation of radionuclides in previously deposited fallout that was resuspended by nuclear detonations at NTS was considered in a report by the National Research Council (NRC, 2003). An analysis in that report was prompted by a finding that resuspension of previously deposited fallout by nuclear detonations had not been considered in

[1] Radioactive materials that were resuspended by an above-ground detonation at NTS generally included neutron activation products in soil from that detonation as well as fallout from previous detonations that was present in areas near ground zero. The presence of soil activation products in resuspended materials is not considered explicitly in this analysis. However, their inclusion would have a negligible effect on our results (Trabalka and Kocher, 2007).

[2] Dancz and Chehata (2006) identified nine shots in Operations TUMBLER-SNAPPER (1952), UPSHOT-KNOTHOLE (1953), and TEAPOT (1955) at which exposure to previously deposited fallout that was resuspended by a nuclear detonation could have occurred. The potential for such exposures at Operation PLUMBBOB (1957) was not considered in that analysis.

dose reconstructions at NTS. Consequently, there was a concern that inhalation doses to affected participants, including forward observers and maneuver troops, could have been underestimated substantially.[3] An example analysis in the NRC report suggested that, depending on the concentrations of radionuclides in previously deposited fallout, inhalation doses to some organs or tissues could have been significant. The example analysis indicated that organs or tissues that could have received significant doses include those at the major sites of deposition of inhaled radionuclides in the body (e.g., lung, bone surfaces, red bone marrow, liver). However, the example analysis also suggested that doses to organs or tissues at minor sites of deposition of inhaled radionuclides (e.g., prostate and many other soft tissues) were insignificant even if exposure to the highest concentrations of radionuclides in previously deposited fallout that could have been resuspended by a detonation occurred.

The assessment of the high-resuspension scenarios of concern to this report involves an analysis of uncertainty in the model that is used to estimate inhalation doses to military participants in any resuspension scenario. On the basis of assumptions about uncertainties in all model parameters, we derive point values of a resuspension factor that should be assumed in dose reconstructions for the scenarios of concern to ensure that point estimates of inhalation dose are credible upper bounds—i.e., that estimated inhalation doses to any organ or tissue are at least upper 95% credibility limits,[4] as required by applicable regulations on methods of estimating dose in Title 32, Part 218 of the Code of Federal Regulations (32 CFR Part 218) and standard operating procedures and policies of the NTPR Program (DTRA, 2007; Case et al., 2008).

More specifically, we derive point values of resuspension factors that should be assumed in estimating inhalation doses in the high-resuspension scenarios of concern to ensure that credible upper bounds of doses are obtained when point estimates of other parameters that are normally assumed in dose reconstructions for any resuspension scenario (e.g., resuspension by

[3] Dose reconstructions at NTS have considered resuspension of previously deposited fallout by such activities as marching or vehicular traffic through a fallout field. However, only fallout from previous shots in the same test series has been been taken into account, and fallout from shots in previous test series has not been included.

[4] In this report, the term "credibility limit" is used, rather than "confidence limit," to indicate that such a limit is based on highly subjective assessments of uncertainties in model parameters, rather than a rigorous statistical analysis of outcomes that might be obtained by repeated measurement.

walking, vehicular traffic, or the wind) are used. The derived resuspension factors are referred to as "effective" resuspension factors to indicate that they do not necessarily correspond to actual resuspension factors that applied to old fallout that could have been inhaled at locations and times of exposure. Rather, they are resuspension factors that should be assumed to ensure that credible upper bounds of inhalation doses are obtained in dose reconstructions for the scenarios of concern. The analysis in this report does not provide estimates of inhalation dose. Such estimates, which could be based on data on concentrations of radionuclides in fallout from various shots, are not needed to derive effective resuspension factors.

Effective resuspension factors derived in this report are intended to be applied to all radionuclides in previously deposited fallout and at any location in one of two broadly defined regions near ground zero of nuclear detonations, which are referred to as the thermal-pulse and blast-wave regions. The former is the region closest to ground zero where the initial intense pulse of thermal radiation had an important effect on resuspension, and the latter is the region beyond the thermal-pulse region where resuspension was caused only by the blast wave (Glasstone and Dolan, 1977) and presumably was substantially lower than in the thermal-pulse region. Separate effective resuspension factors that should be applied in estimating inhalation doses in the two regions at times shortly after a detonation are derived.

Inhalation of resuspended fallout potentially involved many radionuclides that varied in importance depending on the times prior to exposure when fallout from previous shots occurred and the organ or tissue of interest. Furthermore, especially in the blast-wave region, the resuspension factor probably decreased with increasing distance from ground zero. Therefore, in principle, effective resuspension factors that would ensure that credible upper bounds of inhalation dose are obtained in dose reconstructions could depend on the shot at which exposure to resuspended fallout occurred, the organ or tissue of interest, and the distances from ground zero where participants were exposed. However, it is impractical and unnecessary to derive effective resuspension factors that would apply to specific shots, organs or tissues, and distances from ground zero. Rather, the objective is to derive effective resuspension factors that should be assumed in all cases of exposure to fallout that was resuspended by a nuclear detonation in the thermal-pulse or blast-wave region, without regard for the organ or tissue of interest, the

radionuclides that are important contributors to inhalation doses at a given shot, and the specific locations in those regions where participants were exposed. Use of effective resuspension factors for the high-resuspension scenarios of concern that apply to all inhalation exposures in the two broadly defined regions is consistent with the approach to estimating inhalation doses to military participants in other resuspension scenarios (Egbert et al., 1985; NRC, 2003; Raine et al., 2007), where a single resuspension factor is assumed in all cases where a particular type of resuspension scenario applies.

In above-ground detonations at NTS, resuspension of previously deposited fallout also could have been caused by the so-called "afterwind," which is a strong updraft that sucked dirt and debris into the stem of the fireball produced in a detonation as the fireball rose (Glasstone and Dolan, 1977). Resuspension by the afterwind, which occurred after the thermal pulse and blast wave passed, or any other perturbations of surface winds that might have occurred as the fireball rose, is not considered this report.

This report is organized as follows. Section 2 describes the thermal-pulse and blast-wave regions near ground zero of above-ground nuclear detonations at NTS. Section 3 describes the model that is used in dose reconstructions for military participants to estimate inhalation doses due to resuspension of radionuclides and the approach that is used in this report to assess uncertainties in that model when it is applied to resuspension of previously deposited fallout by nuclear detonations. Section 4 presents the analysis of uncertainty in estimated inhalation doses in scenarios that involved resuspension of previously deposited fallout by nuclear detonations. In Section 5, results of our analysis are used to derive effective resuspension factors that should be assumed in the thermal-pulse and blast-wave regions. Section 6 discusses (1) the importance of judgment in deriving effective resuspension factors and the credibility of the results and (2) the applicability of the results, including the extent of the thermal-pulse and blast-wave regions and the time periods after a detonation when effective resuspension factors should be applied in those regions. The concluding section summarizes the results of this analysis.

## 2. DESCRIPTION OF THERMAL-PULSE AND BLAST-WAVE REGIONS

Nuclear detonations at NTS of interest to this study occurred at heights above ground of about 1,500 ft or less (Hawthorne, 1979). Those detonations produced high levels of resuspended surface soil in two distinct regions near ground zero, which we refer to as the thermal-pulse and blast wave regions.[5] Resuspension of surface soil in those regions is illustrated by the photograph in Figure 2-1 at Shot EASY in Operation BUSTER-JANGLE, which was an airdrop test at a height of 1,314 ft (Hawthorne, 1979).

### 2.1 Thermal-Pulse Region

The thermal-pulse region is the region closest to ground zero where the initial intense pulse of thermal radiation that was produced in a nuclear detonation had an important effect on resuspension (Glasstone and Dolan, 1977). In that region, absorption of thermal radiation that was incident on surface soil produced a layer of hot air near the surface, which also included soil particles that were injected into the air as a result of boiling of water in surface soil. The presence of the layer of hot air resulted in the formation of an auxiliary wave, called the "precursor," that preceded the main blast wave and resulted in intense scouring of surface soil (Snow, 1981). Some of the energy in the precursor propagated upward, which resulted in lofting of resuspended soil particles (dust) and other materials to considerable heights. Additional resuspension in the thermal-pulse region was caused by the main blast wave, which lagged the initial thermal pulse by as much as a few seconds at the outer boundary of that region.

In Figure 2-1, the thermal-pulse region is the region where the height of the cloud of resuspended surface soil extends farther above ground than in the region beyond. The height of the dust cloud in the thermal-pulse region is approximately uniform, and there is a clear distinction between the outer edge of this region and the region just beyond where the thermal

[5] In this report, the term "resuspension" is used to describe transfer of surface soil, as well as previously deposited fallout, into the air by any stress of concern, even though this term strictly applies only to the latter materials. The proper term to describe transfer of surface soil that was not deposited on the ground from the atmosphere is "suspension."

pulse was not sufficiently intense to affect resuspension of material on the ground surface. These characteristics of a dust cloud in the thermal-pulse region are seen in photographs of other detonations at NTS (AFLML, 1951).[6]

The thermal-pulse region in which the precursor was formed extended to a distance from ground zero where the peak overpressure at ground level associated with the blast wave was about 6 pounds per square inch (psi) (Glasstone and Dolan, 1977). At any shot, the distance at which the peak overpressure was 6 psi can be estimated from Figure 2-2, which gives the distances of various peak overpressures as a function of the height of burst of a 1-kiloton (kt) detonation (Glasstone and Dolan, 1977; Figure 3.73c).[7] The burst height and distance of a given peak overpressure both scale as the cube root of the yield (Glasstone and Dolan, 1977). For example, at Shot EASY in Figure 2-1, which had a burst height of 1,314 ft and yield of 31 kt (Hawthorne, 1979), the corresponding burst height for a 1-kt detonation, which is called the scaled height-of-burst, is $1{,}314/(31)^{1/3}$, or 418 ft, and the distance at which the peak overpressure from a 1-kt detonation at that height was 6 psi, as estimated from Figure 2-2, is about 1,700 ft. By scaling this distance by the yield of 31 kt, the estimated distance of the 6-psi line at Shot EASY is about 5,300 ft, or 1 mile. From the known burst heights and yields of above-ground detonations at NTS (Hawthorne, 1979), we estimate that the greatest distance of the 6-psi line from ground zero at any shot was about 1.4 miles. This estimate applies at Shot HOOD in Operation PLUMBBOB, which was detonated at a height of 1,500 ft with a yield of 74 kt.

## 2.2 Blast-Wave Region

Beyond the thermal-pulse region, resuspension was caused by the high wind associated with the blast wave that was produced in a nuclear detonation. The high wind, which was

[6] Examples include Shot CHARLIE in Operation BUSTER-JANGLE, Shot CHARLIE in Operation TUMBLER-SNAPPER, Shot MET in Operation TEAPOT, and Shots BOLTZMANN and PRISCILLA in Operation PLUMBBOB.

[7] Calculations represented in Figure 2-2 apply under nearly ideal conditions where effects of terrain, surface properties, and meteorological conditions are unimportant. Although the ground surface at NTS is thermally nonideal, these calculations are considered to be appropriate for general use.

directed away from a detonation, persisted for a few seconds at a given location and was followed by a much weaker and much less important wind that lasted for several seconds and was directed toward the detonation (Glasstone and Dolan, 1977). As indicated in Figure 2-1, the blast-wave region extended well beyond the thermal-pulse region, and the height of the dust cloud was substantially lower than in the thermal-pulse region.

It is difficult to define the outer boundary of the blast-wave region, essentially because the maximum wind speed associated with the blast wave decreased with increasing distance from a detonation and the lowest wind speed that would cause unusually high resuspension when the wind persisted for no more than a few seconds is not well defined. If we assume, for example, that the blast-wave region extended to a distance from ground zero where the maximum wind speed was about 40−70 miles per hour (mph), calculations summarized in Table 2-1 (Glasstone and Dolan, 1977; Table 3.07 and Figure 3.55) indicate that the corresponding peak overpressure was about 1−2 psi. By using the curves in Figure 2-2, with the burst height and distance from ground zero both scaled by the cube root of the yield as discussed in the previous section, we then estimate that the blast-wave region at Shot EASY in Figure 2-1 extended to a distance of about 2−3 miles. At Shot HOOD, which was the worst case noted in the previous section, we estimate that the blast-wave region extended to a distance of about 2.5−4 miles. This estimate is roughly consistent with reports of military activities at Shot HOOD (Maag et al., 1983; USMC, 1957), which indicated that a dense dust cloud probably was formed to a distance of at least 5 miles. At yields of about 10−40 kt and burst heights of 300−500 ft, which were common in detonations at NTS (Hawthorne, 1979), the blast-wave region should have extended to a lesser distance than at Shot HOOD, perhaps by about 20−50%. As at Shot HOOD, it may be possible to define the extent of the blast-wave region at particular shots on the basis of reports of actual conditions at times shortly after detonation.

Estimates of the extent of the blast-wave region given above are intended only as illustrative examples. The issue of defining the extent of the blast-wave region is discussed further in Section 6.2.

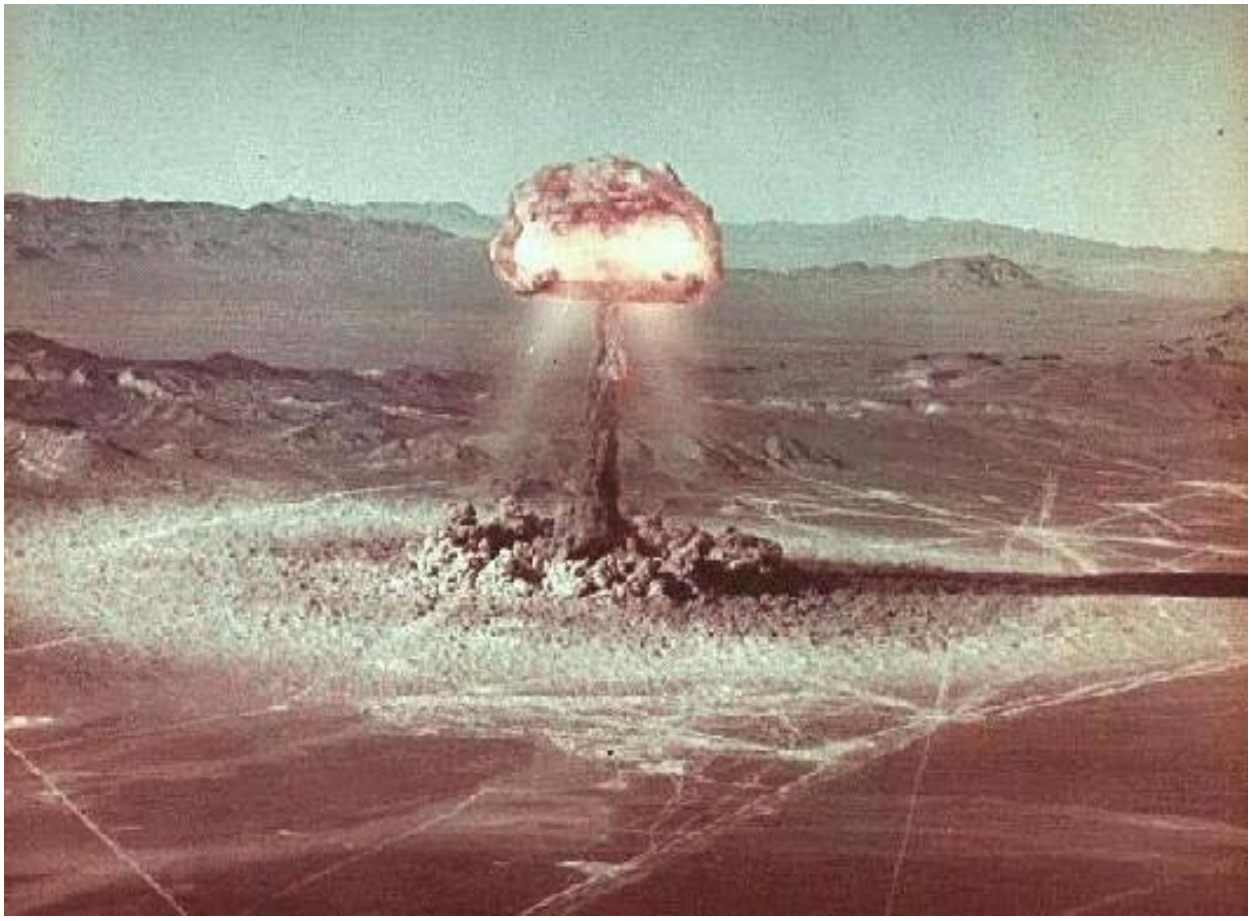

**Figure 2-1.** Photograph of Shot EASY in Operation BUSTER-JANGLE (AFLML, 1951) showing region closest to ground zero where thermal pulse had an important effect on resuspension of surface soil and blast-wave region extending beyond region impacted by thermal pulse where height of resuspended dust cloud was lower.

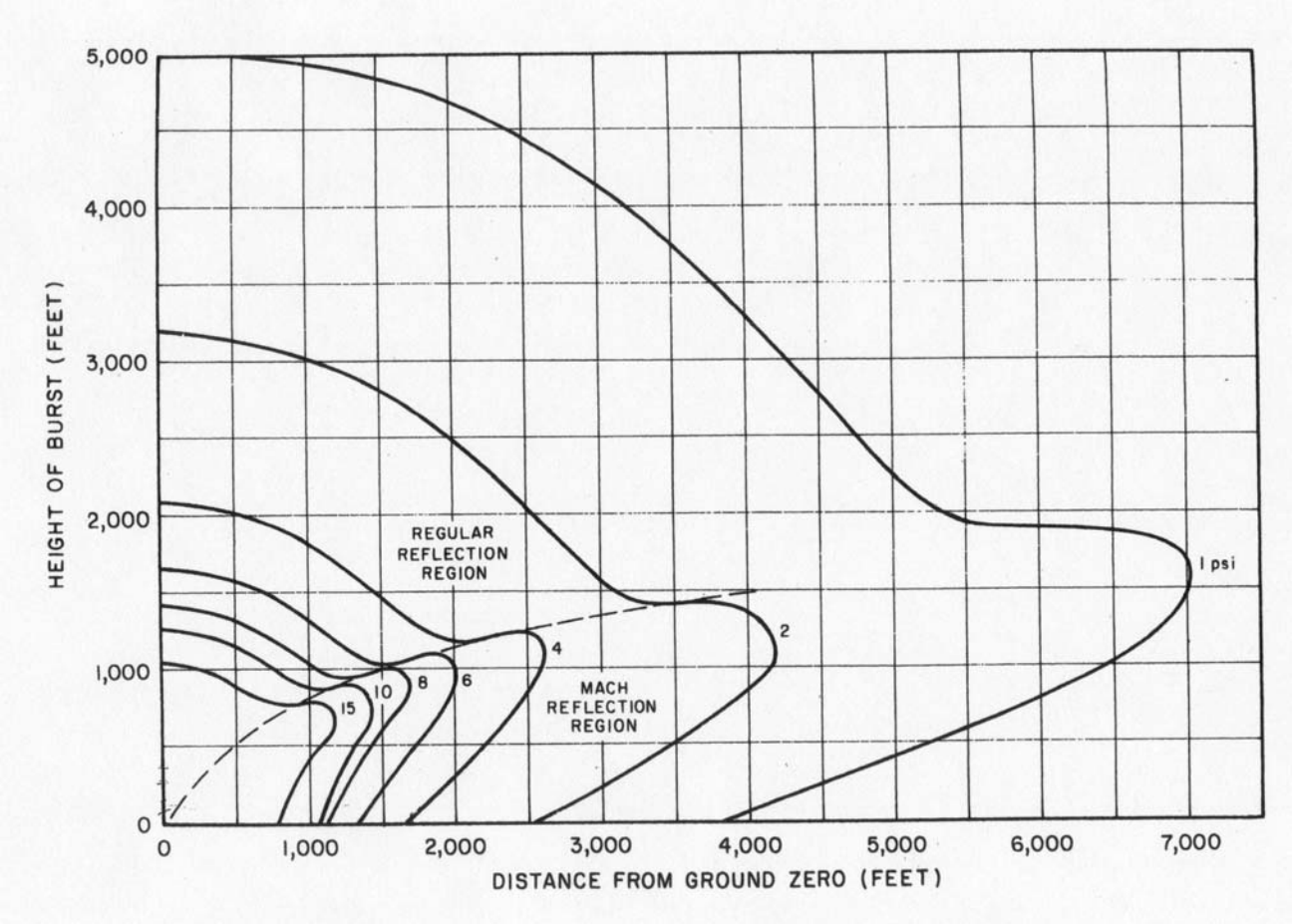


**Figure 2-2.** Dependence of peak overpressure at ground level in pounds per square inch (psi) on height of burst and distance from ground zero for 1-kiloton (kt) detonation (Glasstone and Dolan, 1977; Figure 3.73c). Burst height and distance of a given peak overpressure from ground zero both scale as the cube root of the yield in kt.

**Table 2-1.** Calculated maximum wind speed at various peak overpressures associated with blast wave produced in above-ground nuclear detonations[a]

| Peak overpressure (pounds per square inch) | Maximum wind speed (miles per hour)[b] | Peak overpressure (pounds per square inch) | Maximum wind speed (miles per hour)[b] |
|---|---|---|---|
| 200 | 2,100 | 20 | 500 |
| 150 | 1,800 | 10 | 290 |
| 100 | 1,400 | 5 | 160 |
| 72 | 1,200 | 2 | 70 |
| 50 | 930 | 1 | 40 |
| 30 | 670 | | |

[a] Estimates are obtained from Table 3.07 of Glasstone and Dolan (1977), except maximum wind speed at peak overpressure of 1 psi is obtained from Figure 3.55.

[b] Values are rounded to two significant figures at wind speeds above 100mph and to one significant figure at lower wind speeds.

# 3. APPROACH TO ASSESSMENT OF INHALATION DOSES IN RESUSPENSION SCENARIOS

In this report, the assessment of exposure scenarios that involved inhalation of radionuclides in previously deposited fallout that was resuspended by above-ground detonations at NTS is based on an analysis of uncertainty in the model that is currently used to estimate inhalation doses to military participants in any resuspension scenario. The following sections describe the model and our approach to an uncertainty analysis for the purpose of deriving effective resuspension factors in the thermal-pulse and blast-wave regions that should be assumed in dose reconstructions to obtain inhalation doses that are credible upper bounds (at least upper 95% credibility limits).

## 3.1 Description of Model to Estimate Inhalation Dose

The model that is currently used to estimate inhalation doses to military participants in any scenario that involved resuspension of radionuclides on the ground surface is described by Barrett et al. (1986) and in Section IV.C.2 of the NRC (2003) report.

In any scenario for inhalation exposure, the dose from inhalation of a particular radionuclide is estimated as:

$$D = AA \times BR \times DF \times T\,, \tag{1}$$

where

$D$ = equivalent dose to specific organ or tissue (rem),[8]

$AA$ = activity concentration of radionuclide in air (Ci $m^{-3}$),

[8] Until recently, the dosimetric quantity that was calculated in dose reconstructions for military participants was called "dose equivalent." The term "equivalent dose" is now used in the NTPR Program (DTRA, 2007; Raine et al., 2007) to conform to a recommendation by the International Commission on Radiological Protection (ICRP, 1991) and National Council on Radiation Protection and Measurements (NCRP, 1993).

$BR$ = breathing rate ($m^3\ h^{-1}$),

$DF$ = equivalent dose to specific organ or tissue per unit activity of radionuclide inhaled (rem $Ci^{-1}$),[9]

$T$ = duration of exposure (h).

The dose from inhalation of mixtures of radionuclides is the sum of calculated doses from each radionuclide. The dose from all radionuclides combined is calculated using radionuclide-specific values of the concentration in air, *AA*, and dose coefficient, *DF*.

The model in eq. (1) incorporates an assumption that airborne radionuclides are attached to particles of size sufficiently small that they can be inhaled; i.e., the concentration in air, *AA*, is a value that applies to inhalable materials only. The concentration in air also is time-dependent in most scenarios. Thus, the term *AA* in eq. (1) represents an average concentration of a radionuclide in inhalable form during the period of exposure, *T*.

The dose coefficient, *DF*, depends on the particle size of inhaled material, which is expressed in terms of the activity median aerodynamic diameter (AMAD) of a distribution of particle sizes (ICRP, 1979; 1994). Until recently, an AMAD of 1 or 20 μm was assumed in dose reconstructions for military participants (Egbert et al., 1985), and the assumption that gave the higher dose to an organ or tissue of interest for the assumed mixture of inhaled radionuclides was used. On the basis of the model of the respiratory tract that was used to calculate those dose coefficients (ICRP, 1979), dose coefficients for inhalation of 20-μm particles were essentially the same as dose coefficients for ingestion, because the model assumed that 95% of all inhaled particles with an AMAD of 20 μm are deposited in the nasal passages and that 99% of the deposited material is transferred to the gastrointestinal (GI) tract by swallowing. Therefore, the dose coefficient in eq. (1) was either the value for inhalation of respirable 1-μm particles, which were assumed to be deposited to some extent in all regions of the respiratory tract (ICRP, 1979), or the value for ingestion, which represented the dose coefficient for inhalation of larger particles

[9] Until recently, the quantity *DF* was referred to as a "dose conversion factor" in dose reconstructions for military participants (Egbert et al., 1985). The term "dose coefficient" is now used in the NTPR Program (DTRA, 2007; Raine et al., 2007) to conform to terminology currently recommended by ICRP; e.g., see ICRP (1996a).

that were assumed to be essentially nonrespirable and were not deposited to a significant extent in regions of the respiratory tract other than the nasal passages.

Dose reconstructions for military participants now use dose coefficients for inhalation of radionuclides by adult members of the public that are currently recommended by ICRP [(1996a; 2002) and references therein]; see Raine et al. (2007).[10] These dose coefficients replace those used previously (Egbert et al., 1985), which were based in large part on recommended dosimetric and biokinetic models for workers in ICRP Publication 30 (ICRP, 1979). ICRP's current model of the respiratory tract assumes that about 50% of all large, essentially nonrespirable particles that are inhaled are deposited in the nose and throat and that about 50% of the deposited material is transferred to the GI tract by swallowing, with the deposited material that is not swallowed assumed to be expelled by nose-blowing or -wiping; i.e., about 25% of all large particles that are inhaled are assumed to be swallowed (ICRP, 1994). Therefore, ingestion dose coefficients that were used previously in dose reconstructions probably overestimated doses from inhalation of large, nonrespirable particles by a factor of about 4 in cases where there were no other significant changes in internal dosimetry models for radionuclides of concern. Dose coefficients for inhalation that are now used in dose reconstructions are calculated by assuming a particle size (AMAD) of 1, 3, 5, or 10 μm, and the assumption that gives the highest equivalent dose to an organ or tissue of interest for the assumed mixture of inhaled radionuclides in a particular case is used (Raine et al., 2007). Particles with an AMAD of 10 μm or greater are assumed to be essentially nonrespirable and are either expelled or swallowed (ICRP, 1994).

In this analysis, the inhalation dose per unit exposure time (rem $h^{-1}$) is assessed, because the duration of exposure, $T$, is an extrinsic factor that is determined by an individual's activities and the uncertainty in $T$ is negligible compared with uncertainties in other parameters in the model, especially the average concentration in air during the period of exposure, $AA$, and the dose coefficient, $DF$. The inhalation dose per unit exposure time is given by:

$$\Delta D/\Delta t = AA \times BR \times DF \, . \tag{2}$$

[10] A requirement to use dose coefficients currently recommended by ICRP is contained in the *Policy & Guidance Manual* of the NTPR Program (DTRA, 2007).

Airborne concentrations of radionuclides were not measured during periods of exposure of military participants. In scenarios that involved resuspension of radionuclides, the concentration of a radionuclide in air above ground (Ci $m^{-3}$) is estimated on the basis of an estimate of its concentration on the ground surface and a resuspension-factor model given by:

$$AA = SA \times K , \tag{3}$$

where

$SA$ = activity concentration of radionuclide on ground surface (Ci $m^{-2}$),
$K$ = resuspension factor ($m^{-1}$).

A resuspension factor thus is defined as the ratio of the concentration of a radionuclide in air to its areal concentration on the ground surface. Reported resuspension factors often are based on measured concentrations in air at a height of 1 m above ground.[11] Since the concentration in air should be a value that applies to inhalable materials, resuspension factors should represent airborne concentrations of radionuclides in inhalable form relative to total areal concentrations on the ground surface.

Concentrations of radionuclides on the ground surface, *SA*, also were not measured during periods of exposure. In dose reconstructions, concentrations of radionuclides in deposited fallout are estimated on the basis of (1) measured photon exposure rates in air above ground (R $h^{-1}$) at various locations and times shortly after each detonation, (2) calculated exposure rates per unit activity concentration of each radionuclide on the ground surface (R $h^{-1}$ per Ci $m^{-2}$), and (3) the relative activities of each radionuclide in fallout, which are estimated on the basis of calculated yields in fission, cloud-sampling data, and an assumption that fallout was

[11] When surface soil is resuspended by relatively gentle stressors, such as walking or light vehicular traffic, resuspension factors may decrease substantially with increasing height above ground (Sehmel, 1984; Tables 12.7 and 12.9). Thus, if an individual is standing on the ground, a resuspension factor that applies at the location of the head under those conditions could be substantially lower than a resuspension factor at 1 m. However, the stressors that occurred in nuclear detonations are much more vigorous, and it is not expected that resuspension factors in the thermal-pulse and blast-wave regions varied significantly over the height of an individual standing on the ground.

unfractionated.[12] Photon exposure rates per unit activity concentration of radionuclides on the ground surface are calculated at a height of 1 m by assuming that the source region is a plane of infinite extent (Egbert et al., 1985; Raine et al., 2007). Calculated exposure rates also account for the shielding effect of ground roughness, which is assumed to reduce exposure rates to about 70% of the exposure rates above an unshielded plane source (Egbert et al., 1985; Raine et al., 2007).[13] Thus, activity concentrations of radionuclides on the ground surface are estimated from measured photon exposure rates, $I$ (R $h^{-1}$), as:

$$SA = (SA/I) \times I \,, \tag{4}$$

where $SA/I$ is the reciprocal of a calculated exposure rate at a height of 1 m per unit activity concentration on the ground surface (Ci $m^{-2}$ per R $h^{-1}$). For mixtures of radionuclides with assumed relative activities, $SA/I$ represents the concentration of each radionuclide on the ground per unit exposure rate in air above ground from all radionuclides combined, and $SA$ calculated from eq. (4) represents the concentrations corresponding to a measured exposure rate, $I$.

By combining eqs. (2), (3), and (4), the equivalent dose to an organ or tissue of interest from inhalation of resuspended radionuclides per unit exposure time is given by:

$$\Delta D/\Delta t = I \times (SA/I) \times K \times BR \times DF \,. \tag{5}$$

When resuspension scenarios are included in dose reconstructions, point estimates of all parameters in the model in eq. (5) are used. As noted in Section 1, the assumed parameters should result in credible upper bounds (at least upper 95% credibility limits) of estimated inhalation doses. To comply with this requirement, the selection of resuspension factors that are expected to substantially overestimate concentrations of radionuclides in air relative to concentrations on the ground surface in an assumed scenario is emphasized (Egbert et al., 1985;

[12] Only fission and activation products normally contributed significantly to measured photon exposure rates. Activity concentrations of plutonium in fallout relative to concentrations of fission and activation products in weapons debris are estimated from cloud-sampling data.

[13] To account for the shielding effect of ground roughness, exposure rates in air above ground are calculated by assuming that the source region consists of two plane sources with equal activity concentrations, one source located at a depth of 0.25 cm in soil and the other at a depth of 0.75 cm.

Barrett et al., 1986; NRC, 2003; Raine et al., 2007). Selected values of other parameters in the model are intended to be more realistic.

### 3.2 Approach to Derivation of Effective Resuspension Factors

The purpose of our assessment of exposure scenarios that involved inhalation of radionuclides in previously deposited fallout that was resuspended by above-ground detonations at NTS is to derive point values of effective resuspension factors that should be used in the model in eq. (5) to ensure that credible upper bounds (at least upper 95% credibility limits) of inhalation doses are obtained when point estimates of other parameters that are normally assumed in dose reconstructions for other resuspension scenarios (i.e., concentrations of radionuclides on the ground surface, the breathing rate, and dose coefficients for inhalation) are used. Effective resuspension factors are derived in the following way.

First, probability distributions that are assumed to represent uncertainty in all parameters in eq. (5), including the resuspension factor in the thermal-pulse or blast-wave region, are propagated through the model to obtain a probability distribution that represents uncertainty in model output, and the upper 95% credibility limit of that distribution is identified. Then, by comparing the upper 95% credibility limit with a point estimate of model output obtained by using point estimates of all other parameters that are normally assumed in estimating inhalation doses in other resuspension scenarios, an effective resuspension factor that would give a model output equal to the upper 95% credibility limit obtained in the probabilistic uncertainty analysis is calculated. Effective resuspension factors so derived are rounded to the nearest power of 10 to be consistent with assumed resuspension factors in other scenarios for inhalation exposure at NTS and in the Pacific (Barrett et al., 1986; Phillips et al., 1985). This level of precision is appropriate when resuspension factors in any scenario are highly uncertain.

It is important to emphasize that comparisons of probability distributions of outputs of the model in eq. (5) with point estimates that are obtained in dose reconstructions do not require assumptions about concentrations of radionuclides on the ground surface or inhalation dose coefficients. As indicated by an example analysis in Section V.C.3.3 of the NRC (2003) report,

such comparisons can be based on a unit concentration on the ground surface and a unit inhalation dose coefficient for all radionuclides combined. The key to understanding the analysis in this report is to recognize that it is concerned only with relative comparisons of inhalation doses that are calculated using probability distributions of model parameters with doses that are calculated using point estimates of all parameters.

Uncertainty in output of the model in eq. (5) is estimated using a Monte Carlo sampling method. A probability distribution of each model parameter, which is assumed to represent its uncertainty, is defined, values of each parameter are selected from those probability distributions by repeated random sampling, and parameter values in each random sample are propagated through the model to generate a probability distribution of model output, which represents uncertainty in estimated inhalation doses. We emphasize that assumed probability distributions of model parameters are subjective representations of uncertainty that are based on scientific judgment, rather than distributions that might be obtained by repeated measurement; i.e., they are intended to represent the current state of knowledge. Therefore, estimates of uncertainty in calculated inhalation doses also represent subjective scientific judgment. The need for judgment is a consequence of the paucity of data that can be used to quantify uncertainty in important model parameters. Approaches to uncertainty analysis used in this report, including the importance of judgment, are discussed elsewhere (NCRP, 1996).

The method of Monte Carlo sampling used in this analysis is a form of stratified random sampling called Latin Hypercube sampling (McKay et al., 1979). In this method, probability distributions of model parameters are divided into $N$ intervals of equal probability, where $N$ is the number of random samples used in calculating a probability distribution of model output. In the first iteration, one interval and one value in that interval are selected at random for each parameter, and the model output corresponding to the selected values of all parameters is calculated. In each subsequent iteration, parameters are selected at random in the same way, except intervals previously sampled are excluded. Latin Hypercube sampling thus ensures that the entire probability distribution of each parameter is sampled, thereby providing more robust estimates of probability distributions of model output for a given number of samples than conventional Monte Carlo methods in which parameters are sampled at random in each iteration

without regard for previously sampled values. Sampling over entire probability distributions of parameters is important when upper tails of probability distributions of model output (e.g., upper 95% credibility limits) are of interest, as is the case in the analysis presented in this report.

All probability distributions of model output described in this report were calculated using Crystal Ball® software (Decisioneering, 2001). In all calculations, the number of samples from probability distributions of input parameters was 10,000, and the initial seed value for the random number generator was set to 0. At that number of samples, changes in the initial seed value or the sequence of random numbers for a given initial seed result in variations in upper 95% credibility limits of model output of no more than a few percent.[14] Such variations are unimportant when assumed probability distributions of model parameters are highly subjective and effective resuspension factors that are derived from upper 95% credibility limits of probability distributions of model output are rounded to the nearest power of 10. Crystal Ball® also allows correlations between different parameters to be taken into account in propagating probability distributions of uncertain parameters through a model. The potential importance of parameter correlations to results of our analysis is considered in Section 4.2.5.

The approach to assessing resuspension scenarios at NTS presented in this report is similar to approaches that were used in example analyses in Section V.C.3.3 and Appendix E of the NRC (2003) report. However, the assessment in this report is independent of those analyses, which were intended as hypothetical illustrative examples only, in that we performed our own assessment of uncertainties in model parameters. Some parameter uncertainties developed in this report differ substantially from assumptions used in the NRC report.

[14] Crystal Ball® also allows use of the same sequence of random numbers for a given initial seed value in all calculations. If that option is chosen, the same probability distribution of model output is obtained each time a calculation is performed using the same number of random samples.

# 4. ANALYSIS OF UNCERTAINTIES IN ESTIMATED INHALATION DOSES DUE TO RESUSPENSION BY NUCLEAR DETONATIONS AT NTS

This section presents an analysis of uncertainties in the model in eq. (5) (see Section 3.1) when it is used to estimate inhalation doses in scenarios that involved resuspension of radionuclides in previously deposited fallout by nuclear detonations at NTS. Probability distributions that are assumed to represent uncertainty in each model parameter are developed. Results of propagating those distributions through the model using techniques of random sampling to obtain probability distributions that represent uncertainty in estimated inhalation doses are presented. As described in Section 3.2, these results are used to derive point values of effective resuspension factors that should be assumed in the thermal-pulse and blast-wave regions near ground zero of nuclear detonations to ensure that estimates of inhalation dose are credible upper bounds (at least upper 95% credibility limits) of possible doses to military participants; effective resuspension factors are derived in Section 5.

## 4.1 Assumed Probability Distributions of Model Parameters

With reference to the model in eq. (5), parameters for which subjective probability distributions to represent uncertainty are developed in this analysis include:

- the photon exposure rate in air due to fallout deposited on the ground ($I$),
- areal concentrations of radionuclides in deposited fallout per unit exposure rate in air above ground ($SA/I$),
- the resuspension factor ($K$),
- the breathing rate ($BR$), and
- dose coefficients for inhalation of radionuclides ($DF$).

An accounting of uncertainties in the photon exposure rate ($I$), the resuspension factor ($K$), the breathing rate ($BR$), and dose coefficients for inhalation ($DF$) is straightforward, since doses

from inhalation of resuspended radionuclides are directly proportional to those parameters. However, an accounting of uncertainty in the areal concentrations of radionuclides in deposited fallout per unit exposure rate ($SA/I$) is more complex when several factors that affect estimates of inhalation dose in different ways must be considered.

### **4.1.1** *Photon Exposure Rate Due to Deposited Fallout*

All estimates of inhalation dose in resuspension scenarios are based on measurements of exposure rates in air due to photons emitted by radionuclides on the ground at various locations and times shortly after each detonation. Those measurements are used to generate contour plots of exposure rates at a fixed time after detonation, usually one hour. At any location where exposure occurred, the exposure rate at the fixed time after detonation is estimated using spatial interpolation or extrapolation. The exposure rate, $I$, at any location at the fixed time after detonation is uncertain as a consequence of measurement uncertainty and uncertainty in spatial interpolation or extrapolation of measured exposure rates. Extrapolation of measured exposure rates in time to generate exposure-rate contours at the fixed time is not an additional source of uncertainty when relative activities of radionuclides on the ground are known, because those extrapolations are based on known decay rates (half-lives) of radionuclides (Egbert et al., 1985; Raine et al., 2007). However, there is uncertainty in extrapolations in time that arises from uncertainty in the relative activities of radionuclides in fallout; this uncertainty is addressed in assessing uncertainty in the concentrations of radionuclides in fallout deposited on the ground per unit exposure rate ($SA/I$) in the following section.

In this analysis, estimates of photon exposure rates at any location at a fixed time after detonation that are based on measurements at times shortly after each detonation are assumed to be uncertain by a factor of 3.[15] We represent this uncertainty by a lognormal probability

[15] In this report, a statement that a parameter is uncertain by a factor of $x$ means that the ratio of an upper bound to the median ($50^{th}$ percentile) is $x$, unless otherwise noted. When an unbounded probability distribution (e.g., lognormal or normal) is assumed, the upper bound is the $95^{th}$ percentile (upper 95% credibility limit). When a bounded distribution (e.g., log-triangular or uniform) is assumed, the upper bound is the maximum value, and the $95^{th}$ percentile is somewhat less.

distribution with a 90% credibility interval between 1/3 and 3 times the exposure rate that is assumed in dose reconstructions—i.e., point estimates of exposure rates at a fixed time after detonation that are used in dose reconstructions are assumed to be median values ($50^{th}$ percentiles) of lognormal probability distributions, and the probability that the true exposure rate is within a factor of 3 of the median is assumed to be 90%. The assumed uncertainty is based on a finding in the NRC (2003) report that the uncertainty in reconstructed external photon doses to participants whose exposures were not recorded by film badges usually should be about a factor of 3. The assumed uncertainty is due mainly to the uncertainty in interpolating or extrapolating measurements at a few locations to other locations where exposure occurred, and it is intended to account for any variations in radionuclide concentrations on the ground surface that affect estimates of external exposure rates at locations of exposure.[16]

Uncertainties in measurements of exposure rates using field instruments should be no more than a few tens of percent (Brady and Nelson, 1985) and, thus, should be unimportant.[17] Measurement uncertainty is assumed to be incorporated in the subjective estimate of uncertainty of a factor of 3 that we have assigned to estimated photon exposure rates at locations of exposure to account for uncertainty in extrapolating or interpolating measured values.

An additional consideration in scenarios that involved resuspension of radionuclides by a nuclear detonation is the following. The model used to estimate inhalation doses in resuspension scenarios (see Section 3.1) incorporates an assumption that airborne concentrations of radionuclides at any location resulted from resuspension of radionuclides on the ground at that location. This is a reasonable assumption in many scenarios, such as resuspension by walking or

[16] The uncertainty in the photon exposure rate at many locations could be substantially less than a factor of 3. This could be the case, for example, at locations where exposure rates in fallout fields at NTS that were well characterized are relatively high. However, for purposes of this analysis, a single estimate of uncertainty that applies at any location in a fallout field is needed, and we believe that a factor of 3 is a reasonable representation of that uncertainty. An uncertainty of a factor of 3 also is specified in the *Policy & Guidance Manual* of the NTPR Program (DTRA, 2007). Use of an unbounded lognormal probability distribution gives a small weight (2.5%) to an assumption that the exposure rate was more than a factor of 3 higher than the value assumed in dose reconstructions.

[17] For example, if measurement uncertainty is represented by a normal distribution with a 90% credibility interval between 0.7 and 1.3 times a reported exposure rate, combining this uncertainty with the assumed uncertainty of a factor of 3 in interpolating or extrapolating measured exposure rates to locations of exposure would increase the overall uncertainty by only about 3%.

vehicular traffic. However, nuclear detonations at NTS resulted in resuspension over large areas, and mixing of airborne radionuclides from areas away from a location of exposure by turbulent diffusion and the wind associated with a blast wave, which was initially directed away from a detonation but then reversed direction (see Section 2.2), presumably occurred. Thus, airborne concentrations of radionuclides at any location may have resulted from resuspension over an area in which concentrations on the ground varied substantially.

The issue of concern to our analysis is whether the effect described above is a significant source of additional uncertainty in using measured photon exposure rates to estimate airborne concentrations of resuspended radionuclides. We believe that resuspension over large areas is not a significant source of additional uncertainty if the uncertainty in photon exposure rates due to uncertainty in interpolation and extrapolation of measurements to locations where exposure rates were not measured is represented adequately. Widespread mixing of resuspended material should tend to reduce variations in airborne concentrations in the thermal-pulse and blast-wave regions that would result if concentrations at a given location were due only to resuspension at that location and concentrations on the ground varied substantially with location—i.e., an averaging of airborne concentrations over large areas presumably occurred. Consequently, airborne concentrations over a large area could be estimated based primarily on estimated concentrations on the ground in areas of higher concentration, where the uncertainty in estimated photon exposure rates should be lower. On the basis of this reasoning, we have not included an additional uncertainty to account for resuspension over large areas and widespread mixing of resuspended radionuclides.

### **4.1.2** *Concentrations of Radionuclides on Ground Surface Per Unit Exposure Rate*

Uncertainty in the areal concentrations of radionuclides in deposited fallout per unit exposure rate in air above ground ($SA/I$) arises from several factors that affect estimates of inhalation dose in different ways. In assessing uncertainty in the quantity $SA/I$, it is important to bear in mind that the quantity of interest in estimating inhalation doses is the concentration of radionuclides on the ground surface, $SA$, which is calculated as $(SA/I) \times I$ [see eq. (4)], rather

than *SA*/*I* itself, and that we are interested in the effect of uncertainty in *SA* on estimated doses from inhalation of small, respirable particles or larger, nonrespirable particles (see Section 3.1).

The contribution to uncertainty in the concentrations of radionuclides on the ground surface, *SA*, due to uncertainty in measured exposure rates, *I*, is treated separately in the previous section. The exposure rate essentially is a scaling factor in estimating concentrations of radionuclides on the ground surface—i.e., an over- or underestimate of *I* by some factor will result in an over- or underestimate of *SA* for all radionuclides by the same factor.

Other sources of uncertainty in calculating *SA*/*I* and, thus, concentrations of radionuclides on the ground surface, *SA*, and doses from inhalation of resuspended radionuclides include:

- uncertainty in calculations of photon exposure rates in air above ground per unit concentration of radionuclides on the ground surface, which assume that the source region is an infinite and uniformly contaminated plane surface;
- uncertainty in calculated photon exposure rates per unit concentration of radionuclides on the ground surface due to the finite extent of the source region;
- uncertainty in the shielding effect of ground roughness;
- uncertainty in the relative activities of radionuclides in fallout as that uncertainty affects estimates of dose from inhalation of small, respirable particles or larger, nonrespirable particles.

A probability distribution to represent uncertainty in the concentrations of radionuclides on the ground surface, *SA*, due to uncertainty in estimated concentrations per unit exposure rate, *SA*/*I*, is obtained by combining probability distributions that describe each of these uncertainties.

The first three uncertainties listed above are similar to the uncertainty in the exposure rate, *I*, in that they are scaling factors in estimating concentrations of radionuclides on the ground surface, *SA*, and doses from inhalation of resuspended radionuclides. However, uncertainty in the relative activities of radionuclides in deposited fallout affects estimates of *SA* and doses from inhalation of respirable or nonrespirable particles differently, and this source of uncertainty does

not act as a scaling factor when exposure to mixtures of radionuclides occurs, as is generally the case in exposures to resuspended fallout.

**4.1.2.1** *Uncertainty in Calculated Exposure Rates from Infinite, Uniformly Contaminated Plane Source*. Exposure rates per unit concentration of radionuclides on the ground surface are calculated at a height of 1 m above ground, based on an assumption that exposure rates were measured at that height (Egbert et al., 1985; Raine et al., 2007). There are three sources of uncertainty in photon exposure rates per unit concentration of radionuclides that are calculated by assuming a uniform distribution on an infinite plane surface:

- uncertainty in calculations of photon transport from the source region to a location at a height of 1 m above ground;
- uncertainty in the height above ground where photon exposure rates were measured;
- uncertainty in the energies and intensities of photons emitted by radionuclides.

For photons of energy about 0.1 MeV or greater, which are the most important contributors to external exposure, comparisons of various calculations indicate that the uncertainty in calculations of photon transport to a location 1 m above ground is less than 20% (Eckerman and Ryman, 1983). If we assume that the height above ground where photon exposure rates were measured ranged from 0.5 to 1.5 m, calculations by Beck and de Planque (1968; Figure 9) indicate that the uncertainty in calculated exposure rates per unit concentration of radionuclides on the ground surface is about 10%. Uncertainties in the energies and intensities of important photons emitted by radionuclides in fallout are less than 10% (Kocher, 1981; ICRP, 1983).

On the basis of the uncertainties summarized above, we assume an uncertainty of 20% in calculated photon exposure rates per unit concentration of radionuclides on an infinite and uniformly contaminated plane surface. We represent this uncertainty by a normal probability distribution with a median at 1.0 and a 90% credibility interval between 0.8 and 1.2.

**4.1.2.2** *Uncertainty in Calculated Exposure Rates Due to Finite Extent of Source Region*. An assumption of an infinite source region, which is incorporated in all calculations of photon exposure rates per unit concentration of radionuclides on the ground surface (Egbert et al., 1985;

Raine et al., 2007), results in overestimates of exposure rates per unit concentration from a finite source. Thus, radionuclide concentrations that correspond to a measured exposure rate are underestimated when the source region is finite but an infinite source region is assumed.

Calculations of external dose rates from finite sources that are uniformly distributed on the ground surface (Apostoaei et al., 2000) indicate that reductions in exposure rates compared with the exposure rate from an infinite source could exceed 10% only if the distance to the boundary of the source region is less than about 200 m. Data on fallout patterns at NTS (Hawthorne, 1979) indicate that source regions of concern to this analysis were substantially larger. Therefore, possible reductions in photon exposure rates due to the finite extent of regions of deposited fallout at NTS are assumed to be negligible, and a probability distribution to represent this reduction and its uncertainty is not included in our analysis.

**4.1.2.3** *Uncertainty in Shielding Effect of Ground Roughness*. Calculations of photon exposure rates per unit concentration of radionuclides on the ground surface used in dose reconstructions incorporate an assumption that the shielding effect of ground roughness reduces the exposure rate to about 70% of the exposure rate from an unshielded plane source (Egbert et al., 1985; Raine et al., 2007). If the shielding effect of ground roughness and other terrain irregularities reduced exposure rates by a greater amount than assumed in dose reconstructions, for example, concentrations of radionuclides on the ground surface would be underestimated.

On the basis of measurements and calculations reviewed by Burson and Profio (1977), which apply to various types of contaminated surfaces (paved areas, lawns, gravelled areas, plowed fields, hills, and washes), we assume that the shielding effect of ground roughness at NTS reduced photon exposure rates compared with exposure rates above an unshielded plane source by an uncertain factor that is represented by a uniform probability distribution between 0.5 and 0.9. A reduction in exposure rates by a factor outside this range seems highly unlikely (Burson and Profio, 1977). Since a reduction in exposure rates by a factor of about 0.7 is assumed in dose reconstructions, as noted above, the uncertainty in estimated concentrations of radionuclides on the ground surface, *SA*, due to uncertainty in the shielding effect of ground roughness is assumed to be represented by a uniform probability distribution with a minimum at 0.7/0.9 = 0.78 and a maximum at 0.7/0.5 = 1.4. Thus, we assume that, on average, the shielding

effect of ground roughness that is incorporated in dose reconstructions results in slight underestimates (by about 10%) of concentrations of radionuclides on the ground surface.

Penetration of deposited fallout into surface soil over time, which is often referred to as weathering, would result in reductions in photon exposure rates per unit concentration of radionuclides on the ground compared with exposure rates assumed in dose reconstructions. However, we assume that weathering of fallout had a negligible effect on the uncertainty in exposure rates per unit concentration, because exposure rates that are used to estimate radionuclide concentrations on the ground surface at NTS were measured within a few days of each shot and weathering at an arid site should not be important over such short times.

**4.1.2.4** *Uncertainty in Relative Activities of Radionuclides in Fallout at NTS*. Activity concentrations of radionuclides in deposited fallout that are assumed in dose reconstructions are estimated from measured photon exposure rates in air above ground and an assumption that there was no fractionation of radionuclides, except for removal of noble gases (NRC, 2003). That is, the relative activities of radionuclides in fallout are estimated on the basis of estimates of their abundances or abundances of their precursor radionuclides in weapons debris shortly after a detonation, before chemical and physical separation of different elements, a process referred to as fractionation, occurred;[18] fractionation of fallout from detonations at NTS is discussed, for example, by Hicks (1982; 1990). Abundances of specific radionuclides in weapons debris are estimated on the basis of calculations and data from cloud sampling. Relative activities of fission products that resulted from a known fission mode in a weapon (e.g., fission of $^{239}$Pu or $^{235}$U by an unmoderated spectrum of fission neutrons) are calculated from known fission yields (atoms per fission) of each mass chain produced by that fission mode and radionuclide half-lives and parent/decay-product relationships in each mass chain. Contributions to the activities of fission products from different fission modes in a weapon and the relative activities of activation

[18] The FIIDOS computer code that is used to calculate doses from inhalation or ingestion of radionuclides (Egbert et al., 1985; Raine et al., 2007) includes an option to account for fractionation in estimating concentrations of radionuclides other than noble gases in fallout on the basis of data provided by the user. That option has not been used in dose reconstructions (NRC, 2003).

products and unfissioned weapons material (e.g., plutonium) are estimated from cloud-sampling data. We assume that plutonium is the most important unfissioned weapons material in fallout.[19]

Fractionation of radionuclides in fallout is a complex phenomenon (Freiling et al., 1965), and data on fractionation in fallout from specific shots are not extensive. A simplified and idealized description of fractionation is given by Hicks (1982) and in Section IV.C.2.1.2 of the NRC (2003) report. For purposes of this analysis, the important effect of fractionation is that, compared with unfractionated weapons debris in an atmospheric cloud immediately after an above-ground detonation, fallout at locations close to ground zero (e.g., within the boundary of NTS) was enhanced in refractory elements that have relatively high boiling points (e.g., zirconium, cerium, plutonium) or whose short-lived precursors have high boiling points, due to a tendency of those elements to be dissolved in liquid droplets that formed soon after detonation and, thus, to be dispersed in the volume of larger particles that fell to Earth relatively rapidly. Fallout from above-ground detonations at locations close to ground zero also was depleted in volatile elements that have substantially lower boiling points (e.g., strontium, iodine, cesium) or whose precursors are volatile, due to a tendency of those elements to condense from the gaseous phase at later times and, thus, to be attached to the surface of smaller particles that fell to Earth more slowly and were carried farther from ground zero by the winds.

In this analysis, effects of fractionation of fallout on doses from inhalation of plutonium are considered separately from effects on doses from inhalation of fission and activation products. This distinction is made, in part, because fission and activation products include many radionuclides, some of which are considered to be refractory and others volatile, whereas plutonium is considered to be highly refractory (Freiling et al., 1965; Hicks, 1982), and only fission and activation products contributed to measured photon exposure rates ($I$) that are used to estimate concentrations of radionuclides in fallout deposited on the ground ($SA$). A separate

[19] In this report, the term "plutonium" refers to $^{239}$Pu and $^{240}$Pu combined, because these two isotopes have essentially the same radiological properties (Kocher, 1981; ICRP, 1983). Many weapons that were detonated at NTS also contained uranium that was highly enriched in $^{235}$U. However, since the half-life of $^{235}$U exceeds the half-lives of $^{239}$Pu and $^{240}$Pu by more than a factor of 10,000 (Kocher, 1981; ICRP, 1983), $^{235}$U was radiologically insignificant unless its mass in fallout was about 10,000 times higher than the mass of plutonium, which is highly unlikely. We also note that $^{235}$U was not reported in later measurements of radionuclides in surface soil at NTS (McArthur, 1991).

consideration of plutonium also is warranted when there are sources of uncertainty in internal dosimetry models that are more important for alpha-emitting radionuclides than for fission and activation products. Measurements in surface soil at NTS after the period of weapons testing (McArthur, 1991) indicated that other alpha-emitting radionuclides in fallout (e.g., $^{241}$Am and $^{238}$Pu) were unimportant compared with plutonium.

**4.1.2.4.1** *Effects of fractionation of fission and activation products*. An assessment of the effects of fractionation of fission and activation products on estimates of inhalation dose due to resuspension of previously deposited fallout requires two considerations. The first is the effect of fractionation on estimates of concentrations of radionuclides on the ground surface, which are based on measured photon exposure rates and a calculated exposure rate per unit concentration of each radionuclide. The second is the effect of fractionation on estimates of dose from inhalation of small, respirable particles or larger, nonrespirable particles at concentrations of radionuclides on the ground that correspond to a given exposure rate.[20]

Although fallout from above-ground detonations at NTS generally was enhanced in refractory radionuclides compared with unfractionated weapons debris (Hicks, 1982; Miller, 1969), the extent of fractionation in fallout from particular detonations is not well known and presumably was shot-specific. However, the effects of fractionation of fission and activation products on estimates of inhalation dose due to resuspension of radionuclides in previously deposited fallout can be bounded by assuming an extreme case in which only refractory radionuclides, but none of the volatile radionuclides, were present in fallout at NTS.

A bounding analysis of the effects of fractionation of fission and activation products on doses from inhalation of resuspended radionuclides in respirable or nonrespirable form at NTS was performed by Trabalka and Kocher (2007). That analysis was based on the following assumptions and data sets:

[20] The effect of fractionation on the relative concentrations of radionuclides in fallout probably is correlated to some degree with the effect of fractionation on inhalation doses when it is considered that the greater the degree of fractionation, the greater the fraction of the activity that is attached to larger particles and, thus, the lower the fraction of the activity that is attached to inhalable particles. The importance of such a correlation is considered in Section 4.2.5.

- The dominant fission modes in detonations at NTS were fission of $^{235}U$ or $^{239}Pu$ by spectra of fission neutrons, but in unknown proportions.[21] Thus, it was assumed that uncertain contributions from $^{235}U$ and $^{239}Pu$ fission each could range from 0 to 100%.
- Fission yields (atoms per fission) of radioisotopes in each mass chain produced in fission of $^{235}U$ or $^{239}Pu$ were obtained from England and Rider (1994).
- Production of $^{237}U$ and $^{239}U/^{239}Np$ by neutron activation of $^{238}U$ was included in some calculations but not others. When uranium activation products were assumed to be present in fallout, intermediate yields (atoms per fission) and higher yields that should be bounding were assumed.[22]
- Fission products were assumed to be refractory or volatile on the basis of a classification scheme developed by Hicks (1982; Appendix 2). For the few radionuclides that were classified by Hicks as having both volatile and refractory precursors in their decay chains (e.g., $^{91}Y$, $^{140}Ba$, $^{140}La$, and $^{141}Ce$), half of the fission yield was assumed to be present in refractory material and half in volatile material.[23]
- Effects of fractionation can be assessed by ignoring the presence of activation products other than the uranium activation products $^{237}U$ and $^{239}U/^{239}Np$.[24]
- All radionuclides in fallout at NTS were resuspended to the same extent.

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[21] Relative abundances of fission products from fission of $^{239}Pu$ or $^{235}U$ at each shot at NTS have been estimated on the basis of $^{137}Cs/^{90}Sr$ ratios in cloud-sampling data and data on the yields of those radionuclides in the two fission modes (H.L. Beck, personal communication). Such estimates are not needed in a bounding analysis of the effects of fractionation.

[22] Intermediate yields were 15 atoms of $^{237}U$ and 30 atoms of $^{239}U/^{239}Np$ per 100 fissions, and higher yields were 50 and 100 atoms per 100 fissions, respectively.

[23] Hicks (1982) assumed different proportions of refractory and volatile materials in mass chains 91, 140, and 141. However, since supporting data are limited and highly variable, Trabalka and Kocher (2007) assumed equal proportions of refractory and volatile materials in those mass chains.

[24] Other potentially important activation products include those that were produced by neutron activation of weapons casings, shot towers, and soil (e.g., $^{60}Co$, $^{56}Mn$, and $^{152,154}Eu$). Such activation products can be ignored for purposes of a bounding analysis of effects of fractionation when most are considered to be refractory and including them would reduce differences in external exposure rates and inhalation doses from exposure to refractory radionuclides only compared with exposure to an unfractionated mixture of refractory and volatile radionuclides (Trabalka and Kocher, 2007).

- Calculated photon exposure rates per unit concentration of radionuclides on the ground surface can be represented by effective dose-equivalent rates per unit concentration calculated by Eckerman and Ryman (1993).[25]
- Doses from inhalation or ingestion of radionuclides can be represented by the effective dose (ICRP, 1991),[26] augmented by calculations of equivalent dose to a limited number of organs and tissues (i.e., doses to the lung, red marrow, and pancreas from inhalation; doses to the colon, red marrow, and pancreas from ingestion).[27] Dose coefficients for inhalation or ingestion of radionuclides in oxide form by workers currently recommended by ICRP (2002) were used in all calculations.[28]
- Possible differences in absorption of radionuclides from the lungs or GI tract due to the lower biological availability of refractory radionuclides, which tend to be dispersed in the volume of insoluble fallout particles, compared with volatile radionuclides, which tend to be attached to the surface of particles (Miller, 1964), are not taken into account.[29]

On the basis of these assumptions, the ratio of the photon exposure rate per unit concentration of fission products and uranium activation products on the ground when only

[25] At photon energies of about 0.1 MeV or greater, which are the most important in determining exposure rates, differences between exposure (R) and effective dose equivalent are no more than a few tens of percent (ICRP, 1987; 1996b). Such differences are unimportant for purposes of this analysis.

[26] The effective dose is a weighted average of equivalent doses to many organs and tissues (ICRP, 1991), which replaced the effective dose equivalent (ICRP, 1977). Effective dose equivalents or effective doses have been calculated in dose reconstructions when results are provided for information only, but they are not calculated in dose reconstructions that are used in adjudicating claims for compensation for cancer or other radiogenic diseases.

[27] A rigorous analysis would require consideration of equivalent doses to all organs and tissues. However, such an analysis is impractical when there are many radionuclides in fallout and distributions of dose among various organs and tissues are radionuclide-specific. The lung, red marrow, and colon were selected because they often receive relatively high doses, and the pancreas was selected to represent soft tissues at minor sites of deposition of radionuclides in the body.

[28] Oxide forms are among the least soluble chemical forms of all elements of concern except strontium, and dose coefficients for radionuclides in oxide form are considered appropriate for intakes of relatively insoluble fallout particles (Egbert et al., 1985; Raine et al., 2007).

[29] Such differences are considered in evaluating uncertainties in dose coefficients for inhalation of larger, nonrespirable fallout particles (see Section 4.1.5.4.3).

refractory radionuclides are assumed to be present to the exposure rate per unit concentration when fission products (except noble gases) and activation products are assumed to be unfractionated can be estimated at any time after detonation. Similar ratios of doses from inhalation of respirable or nonrespirable particles per unit concentration of refractory or unfractionated fission products and uranium activation products can be estimated. As discussed in Section 3.1, doses from inhalation of larger, nonrespirable particles can be calculated using dose coefficients for ingestion. These ratios were estimated at times after detonation of 2 days and 4 years to represent the effects of fractionation in fresh fallout at early times and in aged fallout (Trabalka and Kocher, 2007). Only the calculations at 2 days are relevant in assessing effects of fractionation on estimates of the concentrations of radionuclides in deposited fallout, since photon exposure rates used to estimate those concentrations were measured at times shortly after each detonation. However, calculations at both times are relevant to evaluating effects of fractionation on estimates of inhalation dose.

Results obtained from Trabalka and Kocher (2007) of importance to this analysis are summarized as follows:

Time after detonation of 2 days –

- When all volatile radionuclides are assumed to be removed from an unfractionated mixture of fission products and uranium activation products in deposited fallout and only refractory radionuclides are assumed to be present, the external dose rate above ground is reduced by a factor between 0.37 (fission of $^{239}$Pu, fission products only) and 0.62 (fission of $^{235}$U, fission products plus higher yields of uranium activation products). Thus, to give a known exposure rate at 2 days, concentrations of refractory radionuclides need to be increased by a factor between 1/0.62 = 1.6 and 1/0.37 = 2.7 compared with their concentrations in an unfractionated mixture, depending on the fission mode and the yields of uranium activation products.
- When only refractory fission and activation products are assumed to be present and their concentrations are increased by a factor that would give a known exposure rate at 2 days, as described above, the effective dose from inhalation of respirable particles would

change compared with the effective dose from an unfractionated mixture by a factor between 1.0 (fission of $^{239}$Pu, fission products only) and 1.3 (fission of $^{235}$U or $^{239}$Pu, fission products plus either yields of uranium activation products). Changes in the effective dose from inhalation of nonrespirable particles varied by a factor between 0.64 (fission of $^{239}$Pu, fission products only) and 0.94 (fission of $^{235}$U or $^{239}$Pu, fission products plus higher yields of uranium activation products). When calculations of equivalent dose to a limited number of organs and tissues are included, changes in the effective dose or equivalent dose to a specific organ or tissue ranged from a factor of 0.96 to 1.7 for inhalation of respirable particles and 0.64 to 1.7 for inhalation of nonrespirable particles.

Time after detonation of 4 years –

- When only refractory fission and activation products are assumed to be present and their concentrations are increased by a factor that would give a known exposure rate at 2 days, as described above, the effective dose from inhalation of respirable particles would change compared with the effective dose from an unfractionated mixture by a factor between 0.50 (fission of $^{239}$Pu, fission products plus higher yields of uranium activation products) and 1.4 (fission of $^{235}$U, fission products only). Changes in the effective dose from inhalation of nonrespirable particles varied by a factor between 0.19 (fission of $^{235}$U or $^{239}$Pu, fission products plus higher yields of uranium activation products) and 0.29 (fission of $^{239}$Pu, fission products only). When calculations of equivalent dose to a limited number of organs and tissues are included, increases in the effective dose or equivalent dose to a specific organ or tissue could be as high as a factor of 1.9 for inhalation of respirable particles and 1.1 for inhalation nonrespirable particles.

In the calculations at 4 years, reductions of more than a factor of 100 in equivalent doses to specific organs or tissues were obtained in some cases when only refractory fission and activation products are assumed to be present, including doses to red marrow and the pancreas from inhalation of nonrespirable particles (Trabalka and Kocher, 2007). Those results are not used in this analysis, because our primary concern is the extent to which fractionation could

increase inhalation doses compared with doses calculated in dose reconstructions. Furthermore, if fractionation reduced doses to specific organs or tissues from inhalation of fission and activation products by a large factor, it is all the more likely that plutonium was the most important radionuclide in fallout that had been aged a few years (NRC, 2003) and, thus, that uncertainties in doses from fission and activation products would be unimportant.

If fallout at NTS consisted of refractory radionuclides only, results of the calculations at 2 days and 4 years after detonation summarized above indicate the following. At times shortly after detonation, doses from inhalation of fission and activation products in respirable form would change by a factor between 1.0 and 1.7 and doses from inhalation of fission and activation products in nonrespirable form would change by a factor between 0.6 and 1.7 compared with the corresponding doses from inhalation of an unfractionated mixture of fission and activation products. At times long after detonation, changes in doses would be a factor between 0.5 and 1.9 for inhalation of respirable particles and between 0.2 and 1.1 for inhalation of nonrespirable particles. Thus, the largest potential change in inhalation dose due to fractionation of fission and activation products is assumed to be a factor of 5 (i.e., 1/0.2).

A result that fractionation of fission and activation products could change doses from inhalation of radionuclides in previously deposited fallout at NTS by no more than a factor of 5, when large reductions in equivalent doses to some organs or tissues noted above are excluded, is reasonable when many refractory and volatile fission products were present in fallout and their radiological properties (energies and intensities of emitted radiations) and biokinetic behavior in the body are independent of their fractionation characteristics. Effects of fractionation on doses from individual radionuclides, which can be large and are highly variable, tend to be averaged when many fission products of both types are inhaled. If we consider calculated effective doses, for example, the largest changes are seen in doses from inhalation of nonrespirable particles at 4 years after detonation. Relatively large reductions in effective doses in that case are a consequence of the few refractory fission products that are present in significant activities at that time, compared with the number of volatile fission products, and the relatively low effective dose coefficients for ingestion of longer-lived refractory fission products. Smaller changes are seen in effective doses from inhalation of respirable particles at 4 years, even though only a few

refractory fission products are present at that time, essentially because the effective dose coefficient for nearly all fission products is determined primarily by the dose to the lung when all radionuclides are assumed to be in oxide form and oxide forms of most elements are insoluble.

We assume that the bounding analysis of the effects of fractionation of fission and activation products on inhalation doses at 2 days and 4 years after detonation described above can be used to bound these effects at any time after detonations that produced fallout at NTS. We use results of the bounding analysis to develop probability distributions of factors to adjust estimates of inhalation dose that are obtained by assuming no fractionation of fission and activation products in fallout to account for an enhancement of refractory relative to volatile radionuclides in fallout at NTS. We assume that these factors can be represented by uniform probability distributions with ranges that are defined by the highest and lowest bounding estimates of the effects of fractionation given above. An assumption of uniform probability distributions between those bounding estimates is based on considerations that (1) the relative importance of the assumed fission modes (fission of $^{235}U$ or $^{239}Pu$ by spectra of fission neutrons) is unknown to us and was shot-specific, (2) the degree of fractionation of fission and activation products in fallout at NTS is largely unknown (i.e., the effects of fractionation could range from a bounding value obtained by assuming that only refractory radionuclides were present to the value 1.0 if very little fractionation occurred), and (3) the use of single adjustment factors that apply to inhalation of respirable or nonrespirable particles separately at any time after detonation from a few days to a few years is desirable in estimating doses due to resuspension of radionuclides by a subsequent nuclear detonation when fallout at any location of interest at NTS may have resulted from multiple detonations at various times.

On the basis of the analysis summarized above, we assume that factors to account for the uncertain effects of fractionation of fission and activation products on doses from inhalation of those radionuclides in respirable or nonrespirable form can be represented by the following probability distributions:

- Inhalation of fission and activation products in respirable form – Uniform distribution between 0.5 and 1.9;

- Inhalation of fission and activation products in nonrespirable form – Uniform distribution between 0.2 and 1.7.

Thus, fractionation is assumed to increase or decrease doses from inhalation of fission and activation products compared with doses from an unfractionated mixture. The median and mean of the assumed distributions are 1.2 and 0.95, and the maximum values are less than 2. Thus, we assume that the extent to which fractionation could increase doses from inhalation of fission and activation products, compared with doses from inhalation of unfractionated mixtures, is small.

**4.1.2.4.2** *Effects of enhancement of plutonium*. As noted in Section 4.1.2.4, plutonium was the most important alpha-emitting radionuclide in fallout at NTS, and it probably was the most important radionuclide in resuspended fallout that had been aged a few years (NRC, 2003). Plutonium is highly refractory (Freiling et al., 1965; Hicks, 1982) and its concentrations in fallout at NTS thus were enhanced compared with concentrations in unfractionated weapons debris. In contrast to fission and activation products, which include many radionuclides, an enhancement in the concentrations of plutonium in fallout by some factor results in an increase in inhalation doses by the same factor. Since concentrations of plutonium in fallout that are assumed in dose reconstructions are based on cloud-sampling data and an assumption that fallout was unfractionated (except for removal of noble gases), doses from inhalation of resuspended plutonium presumably have been underestimated.

The extent to which concentrations of plutonium in fallout at NTS were enhanced due to fractionation of weapons debris presumably was shot-specific, and we did not have access to data that could be used to estimate the extent of enhancement compared with an assumption of no fractionation. On the basis of measured volatile-to-refractory mass ratios in off-site fallout from Shots DIABLO, SHASTA, and SMOKY in Operation PLUMBBOB at distances up to 160 miles, Hicks (1982) concluded that about half of the mass of refractory radionuclides from tower shots was present in off-site fallout, which implies that about half of the mass of refractory radionuclides was deposited closer to ground zero. At the closest distance to ground zero of about 5 miles at which data reported by Hicks (1982) were obtained, the volatile-to-refractory mass ratio was about 1.1. When that ratio is compared with an estimated ratio of about 1.4 in

unfractionated fallout (Hicks, 1982), an enhancement in refractory radionuclides by less than a factor of 2 is indicated. However, data used by Hicks (1982) show increasing enhancements of refractory radionuclides with decreasing distance from ground zero, and only one measurement at distances closer than 15 miles was reported. Therefore, substantially greater enhancements of refractory radionuclides in fallout at distances closer than 5 miles are not ruled out. In addition, data used by Hicks may not apply to fallout from other tower shots at NTS.

In the absence of definitive data from all shots and at various distances close to ground zero of interest in dose reconstructions, a bounding estimate of the extent of enhancement of plutonium in fallout at NTS can be obtained from the analysis of the effect of fractionation on external dose rates in air above ground (Trabalka and Kocher, 2007) described in the previous section. That analysis indicated that concentrations of refractory fission and activation products that would give a known external dose rate when all volatile radionuclides are removed are a factor between 1.6 and 2.7 higher than the concentrations in an unfractionated mixture that would give the same external dose rate. Thus, if there were no uncertainty in cloud-sampling data that were used to estimate activities of plutonium relative to activities of fission and activation products, fractionation would enhance the concentrations of plutonium in fallout by no more than a factor of 2.7. Since the extent of fractionation is unknown, its effect on concentrations of plutonium in fallout is represented by a uniform probability distribution between 1.0 and 2.7 in the absence of uncertainty in cloud-sampling data.

There also is uncertainty in the activities of plutonium relative to the activities of fission and activation products due to uncertainty in cloud-sampling data. This uncertainty is assumed to be represented by a standard deviation of 30%.[30] To account for this uncertainty, we increase the upper bound of the uniform probability distribution given above from 2.7 to 3.3.[31]

On the basis of considerations described above, we assume that the enhancement in the concentrations of plutonium in fallout at NTS due to fractionation is represented by a uniform probability distribution between 1.0 and 3.3. The median and mean of this distribution of 2.2 is

[30] H.L. Beck, personal communication.

[31] This increase was obtained by combining a uniform distribution between 1.0 and 2.7 with a normal distribution with a mean at 1.0 and standard deviation of 0.3 and setting the upper 95% credibility limit of the resulting distribution at the 95$^{th}$ percentile of a uniform distribution with a lower bound at 1.0.

consistent with data from three tower shots in Operation PLUMBBOB that were used by Hicks (1982), as discussed above. The assumed probability distribution also represents the uncertainty in increases in doses from inhalation of plutonium in respirable or nonrespirable form compared with doses obtained by assuming that fallout was unfractionated.

**4.1.2.5** *Summary of Uncertainties in Concentrations of Radionuclides in Fallout Deposited on Ground Surface*. Table 4-1 summarizes assumed uncertainties in the different factors that contribute to uncertainty in estimated concentrations of fission and activation products or plutonium in deposited fallout at NTS per unit exposure rate in air above ground, $SA/I$, in eq. (5) and, thus, uncertainty in estimated activity concentrations, $SA$. Table 4-1 also gives the assumed uncertainty in the exposure rate, $I$, discussed in Section 4.1.1.

Representations of uncertainties in concentrations of fission and activation products or plutonium in deposited fallout, which are used as input to calculations of dose from inhalation of resuspended radionuclides in respirable or nonrespirable form, are obtained by combining (multiplying) the probability distributions of relevant parameters in Table 4-1. When probability distributions are combined using Latin Hypercube sampling as discussed in Section 3.2, the following medians and 90% credibility intervals of probability distributions of concentrations of radionuclides on the ground as they affect estimates of inhalation dose are obtained:

- Inhalation of fission and activation products in respirable form – Median at 1.2 and 90% credibility interval between 0.32 and 4.4;
- Inhalation of fission and activation products in nonrespirable form – Median at 0.93 and 90% credibility interval between 0.19 and 3.5;
- Inhalation of plutonium in respirable or nonrespirable form – Median at 2.2 and 90% credibility interval between 0.60 and 7.7.

Thus, we estimate that upper 95% credibility limits of concentrations on the ground surface, $SA$, in eq. (5) exceed point estimates used in dose reconstructions by factors of 4.4 for inhalation of fission and activation products in respirable form, 3.5 for inhalation of fission and activation products in nonrespirable form, and 7.7 for inhalation of plutonium in either form.

The importance of the assumed uncertainty in a parameter to the total uncertainty in *SA* can be represented by its contribution to the variance. The uncertainty of a factor of 3 in estimated exposure rates that are based on measurement contributes 72% and 56% of the total uncertainty in *SA* for fission and activation products in respirable and nonrespirable form, respectively, and 76% for plutonium; this source of uncertainty thus is the most important. Uncertainty in the effects of fractionation contributes 22% and 39% of the total uncertainty for fission and activation products in respirable and nonrespirable form, respectively, and 18% for plutonium. The other two sources of uncertainty contribute 5−7% of the total uncertainties for fission and activation products or plutonium.

All probability distributions of radionuclide concentrations on the ground, *SA*, described above are represented reasonably well by lognormal distributions with the indicated 90% credibility intervals. This is an expected result when the parameter with the largest uncertainty in each case (the exposure rate, *I*) is assumed to be lognormally distributed. The greatest deviation from a lognormal distribution occurs in the case of inhalation of fission and activation products in nonrespirable form, where the probability distribution of *SA* is the most influenced by the uniform probability distribution that represents uncertainty in the effects of fractionation. Geometric standard deviations (GSDs) of lognormal probability distributions with the indicated 90% credibility intervals are about 2.2 for fission and activation products in respirable form, 2.4 for fission and activation products in nonrespirable form, and 2.2 for plutonium in either form.

In these results and all other results presented in this report, 90% credibility intervals of calculated probability distributions have greater significance than medians. This conclusion is based on the consideration that assumed shapes of probability distributions of input parameters are highly subjective in many cases.

### **4.1.3** *Resuspension Factors*

Quantities of interest in estimating inhalation doses due to resuspension of previously deposited fallout by nuclear detonations at NTS are the concentrations of radionuclides in air that could be inhaled at times and locations of exposure. Estimation of those concentrations requires

assumptions about (1) the extent of resuspension of all previously deposited fallout in the thermal-pulse or blast-wave region, which is described by a resuspension factor, and (2) the inhalable fraction of resuspended radionuclides. The latter assumption takes into account that some radionuclides in resuspended fallout presumably were attached to particles that were too large to be inhaled or to be present in air at times after a detonation when exposure occurred.

Inhalation doses also depend on whether inhalable radionuclides were in respirable or nonrespirable form (see Section 3.1). Thus, the inhalable fraction of resuspended radionuclides needs to be separated into respirable and nonrespirable fractions.

In estimating inhalation doses in the thermal-pulse or blast-wave region, the appropriate resuspension factor is the product of the resuspension factor that applies to all fallout on the ground surface and the respirable or nonrespirable fraction of resuspended radionuclides. As discussed in Section 3.1, a resuspension factor that applies to radionuclides in respirable form is appropriate when doses to military participants are estimated by assuming inhalation of small particles with an AMAD less than about 10 μm, and a resuspension factor that applies to radionuclides in nonrespirable form is appropriate when doses are estimated by assuming inhalation of larger particles that are either swallowed or expelled.

**4.1.3.1** *Resuspension of Previously Deposited Fallout*. Resuspension of radionuclides in previously deposited fallout by the thermal pulse/precursor and blast wave in nuclear detonations at NTS presumably was higher than resuspension by less vigorous disturbances. However, we are not aware of any data on resuspension factors associated with the stressors of interest. Therefore, judgment is required in developing a probability distribution of the resuspension factor that applies to all previously deposited fallout in the thermal-pulse or blast-wave region. We develop separate probability distributions of resuspension factors in the two regions on the basis of data on resuspension factors associated with several types of less vigorous disturbances and other assumptions.

**4.1.3.1.1** *Resuspension factor in thermal-pulse region*. Data on resuspension factors associated with a variety of mechanical stresses were reviewed by Sehmel (1984; Table 12.9); see also Sehmel (1980; Figure 2). The most relevant data for purposes of this analysis were obtained at various sites where nuclear weapons were tested, including NTS. Those data are

summarized in Table 4-2. Data on resuspension factors in indoor environments reviewed by Sehmel (1984) are not considered, because surfaces of floors are different in texture from surface soil and resuspension into confined air spaces occurred. Data in Table 4-2 indicate, for example, that at a height of 1 m, a resuspension factor associated with vehicular traffic as high as about $10^{-4}$ $m^{-1}$ is plausible.[32]

We assume that the highest resuspension factor at a height of 1 m associated with vehicular traffic of about $10^{-4}$ $m^{-1}$ provides a lower credibility limit of the resuspension factor that applies to all previously deposited fallout in the thermal-pulse region. Data in Table 4-2 and other data on resuspension of plutonium from safety shots at NTS (Anspaugh et al., 1975) suggest that penetration of fallout into surface soil over time could have reduced the resuspension factor that should be applied to aged fallout to lower values. However, measurements at NTS also suggested that more than 95% of all plutonium in fallout was retained in the top quarter inch (about 0.6 cm) at 1.5 years after deposition (Dick and Baker, 1961). Therefore, since stressors in the thermal-pulse region, including the thermal pulse, precursor, and blast wave with associated wind speeds that exceeded 200 mph (see Table 2-1), presumably were more effective than vehicular traffic in resuspending material located within about 1 cm of the ground surface, we assume that penetration of fallout into surface soil over time was not an important factor in determining resuspension in the thermal-pulse region during time periods after deposition of concern in dose reconstructions. The earliest shots that produced fallout at NTS occurred in 1951 (Hawthorne, 1979), and exposures in the thermal-pulse or blast-wave region occurred as late as 1957 (NRC, 2003). Therefore, the time period between deposition and subsequent resuspensions of concern is about 6 years or less.

We then assume that an upper credibility limit of the resuspension factor that applies to all previously deposited fallout in the thermal-pulse region is $10^{-2}$ $m^{-1}$. This assumption is supported by the following argument. On the basis of an estimate that the diameter of the

[32] Resuspension factors at a height of 0.3 m in Table 4-2, which are as high as $10^{-3}$ $m^{-1}$, should be interpreted with caution, because values at a height of 1 m associated with wind-driven resuspension may be substantially less than resuspension factors at 0.3 m (Stewart, 1967). Data summarized in Table 4-2 do not indicate whether resuspension factors associated with mechanical stresses were substantially lower at the normal height of the head of an individual standing on the ground than at 1 m.

fireball produced in a 20-kt detonation was about 500 m [Glasstone and Dolan (1977), as summarized by Walker (2004)] and photographs of fireballs and dust clouds at times shortly after above-ground detonations at NTS (AFLML, 1951), such as shown in Figure 2-1, we estimate that the height of the dust cloud in the thermal-pulse region was in the range of about 100−300 m. At the lower height of 100 m, a resuspension factor of $10^{-2}$ $m^{-1}$ corresponds to an assumption that all fallout on the ground surface was resuspended, which clearly is an upper bound. At a height of 300 m, the maximum resuspension factor obtained by assuming that all fallout was resuspended is $(1/3) \times 10^{-2}$ $m^{-1}$. However, a somewhat higher resuspension factor could still apply within a few meters of the ground surface if airborne concentrations of resuspended material were lower near the top of the dust cloud in the thermal-pulse region than near the ground.

On the basis of the considerations described above, we assume that the resuspension factor that applies to all previously deposited fallout in the thermal-pulse region of nuclear detonations at NTS is represented by a lognormal probability distribution with a 90% credibility interval between $10^{-4}$ and $10^{-2}$ $m^{-1}$. The median of this distribution is $10^{-3}$ $m^{-1}$ and the GSD is about 4.1. If we assume a nominal height of a resuspended dust cloud in that region of 100 m and a uniform distribution of dust with height, the median resuspension factor corresponds to an assumption that 10% of all fallout on the ground surface was resuspended. At the lower credibility limit of the resuspension factor, 1% of all fallout on the ground is assumed to be resuspended; we believe that this is a reasonable result given the violent nature of stressors in the thermal-pulse region.

Support for the assumed 90% credibility interval of the resuspension factor that applies to all previously deposited fallout in the thermal-pulse region is provided by measurements of airborne concentrations of resuspended dust at Operation TEAPOT, Shot MET (Gordon et al., 1957), which was a 22-kt tower shot at a height of 400 ft (Hawthorne, 1979). At distances from ground zero of 2,000 and 2,500 ft, which were within the thermal-pulse region that extended to a distance of about 3,900 ft as estimated from Figure 2-2, concentrations of airborne dust at heights of 3 and 10 ft ranged from 0.05 to 2 mg $cm^{-3}$. If we assume somewhat arbitrarily that the top 1 cm of soil of density about 1.5 g $cm^{-3}$ was subject to resuspension, the concentrations of

airborne dust correspond to a resuspension factor of about 0.003–0.13 $m^{-1}$. Given the substantial uncertainties in the measured concentrations of airborne dust and the depth of surface soil that was subject to resuspension, we believe that the estimated range of the resuspension factor based on measurement provides some support for our assumed 90% credibility interval.

**4.1.3.1.2** *Resuspension factor in blast-wave region*. In the blast-wave region, the resuspension factor that applies to all previously deposited fallout presumably was less than in the thermal-pulse region, due to the absence of a thermal pulse and precursor and the lower wind speeds associated with a blast wave. In addition to the lack of measurements under conditions of a high-speed burst of wind of short duration, estimation of a resuspension factor is complicated by (1) the decrease in the maximum wind speed associated with a blast wave with increasing distance from ground zero (see Section 2.2 and Table 2-1) and (2) the likely dependence of the resuspension factor on the maximum wind speed, given that concentrations of resuspended material in arid environments typically increase with increasing wind speed at wind speeds lower than maximum values associated with a blast wave (Sehmel, 1984; Table 12.10). Therefore, the resuspension factor at the inner boundary of the blast-wave region, where the peak overpressure was about 6 psi and the maximum wind speed associated with a blast wave was nearly 200 mph (see Table 2-1), probably was substantially higher than at greater distances from ground zero, where the maximum wind speed that could have caused unusually high resuspension perhaps was in the range of about 40–70 mph (see Section 2.2).[33]

For purposes of this analysis, we believe that it is appropriate to develop a single probability distribution to represent an average resuspension factor that applies to all previously deposited fallout throughout the blast-wave region. This approach takes into account that participants who entered the blast-wave region shortly after a detonation were exposed to resuspended radionuclides over a range of distances from ground zero and for varying durations

[33] If the resuspension factor is assumed to increase with wind speed, $u$, as $u^{2.5}$, where the exponent is a nominal value based on data reported by Sehmel (1984; Table 12.10), the resuspension factor in the outermost portions of the blast-wave region would be about 1–2 orders of magnitude less than at the inner boundary, depending on the assumption about the lowest maximum wind speed in the blast-wave region. However, observed dependencies of the resuspension factor on wind speed, which are highly variable, may not apply at higher wind speeds in the blast-wave region, in part because available data apply mainly to resuspension of small, respirable particles, whereas larger particles presumably were resuspended to a greater extent at higher wind speeds, especially near the thermal-pulse region.

at different distances, and that there are no data on the dependence of the resuspension factor on wind speed at the maximum wind speeds of short duration in the blast-wave region. Thus, it is difficult to justify the use of a resuspension factor in the blast-wave region that varies with distance from ground zero.

Data on resuspension factors associated with wind stresses were reviewed by Sehmel (1984; Table 12.7); see also Sehmel (1980, Figure 2), Shinn et al. (1986), and Nicholson (1988). Reported resuspension factors range from about $10^{-10}$ to $3 \times 10^{-4}$ $m^{-1}$. As in the data on resuspension factors associated with mechanical stresses summarized in Table 4-2, the highest value in that range applied at a height of 0.3 m, and the highest value at a height of 1 m is lower (about $5 \times 10^{-5}$ $m^{-1}$). However, available data on wind-driven resuspension probably have limited relevance to this analysis when they apply at wind speeds less than 25 mph, which are much lower than maximum wind speeds in the blast-wave region. In addition, most of the data apply under conditions of chronic wind stress, and some of the data, including some data on resuspension of plutonium at NTS (Shinn et al., 1986), apply at times of a few decades after deposition, when long-term weathering probably reduced resuspension by the wind.

Data on resuspension factors associated with mechanical stresses, as discussed in the previous section and summarized in Table 4-2, also may be relevant in developing a resuspension factor in the blast-wave region. In particular, we believe that it is reasonable to assume that the resuspension factor in areas of the blast-wave region closest to the thermal-pulse region, where the maximum wind speed was the highest, could have been substantially higher than resuspension factors associated with vehicular traffic.

A 90% credibility interval of the resuspension factor in the blast-wave region is estimated on the basis of the following considerations:

- The resuspension factor in the blast-wave region should be substantially lower than in the thermal-pulse region.
- The concentration of resuspended material at the inner boundary of the blast-wave region should be about the same as the concentration in the thermal-pulse region (i.e., the concentration should not be grossly discontinuous at that boundary). Thus, if the height

of the dust cloud at the inner boundary of the blast-wave region is less than the height of the cloud in the thermal-pulse region by some factor, the resuspension factor at the inner boundary of the blast-wave region would be less than the resuspension factor in the thermal-pulse region by about the same factor.

- The uncertainty in the resuspension factor in the blast-wave region should be substantially higher than the uncertainty in the thermal-pulse region, due to the likely dependence of the resuspension factor on the maximum wind speed, which decreases with increasing distance from ground zero, and the likelihood that the resuspension factor decreases with increasing age of the previously deposited fallout, especially in areas of the blast-wave region where the maximum wind speed was relatively low.

On the basis of these considerations, we assume that the resuspension factor that applies to all previously deposited fallout in the blast-wave region can be represented by a lognormal probability distribution with a 90% credibility interval between $10^{-7}$ to $10^{-3}$ $m^{-1}$. The median of this distribution is $10^{-5}$ $m^{-1}$ and the GSD is about 16. Since the height of the dust cloud in the blast-wave region was substantially lower than in the thermal-pulse region and perhaps was a few tens of meters at most (see Figure 2-1), the upper 95% credibility limit of the assumed probability distribution corresponds to an assumption that no more than a few percent of fallout was resuspended to a height of at least 1 m by a blast wave. The assumed probability distribution overlaps higher resuspension factors associated with mechanical stresses (e.g., vehicular traffic; see Table 4-2) and higher resuspension factors associated with wind stresses (Sehmel, 1984). We believe that these comparisons provide support for our assumption.

**4.1.3.1.3** *Discussion of resuspension factors for previously deposited fallout*. Assumed probability distributions of resuspension factors that apply to all previously deposited fallout in the thermal-pulse or blast-wave region developed in the previous two sections are based in part on observations and assumptions about the extent of resuspension of surface soil in the two regions, especially the height of the resulting dust clouds. Thus, those probability distributions incorporate an implicit assumption that resuspension factors that apply to fallout and surface soil are similar.

Several studies, including studies of plutonium and other radionuclides at NTS, have shown that, under certain conditions, resuspension of previously deposited radioactive material can be significantly different from resuspension of surface soil (Shinn et al., 1986; Shinn, 1992; NCRP, 1999, and references therein). In models of resuspension, such differences are represented by an enhancement factor, which is defined as the ratio of the activity per unit mass of airborne particles to the activity per unit mass in surface soil (NCRP, 1999). Studies reviewed by NCRP (1999) have shown the following. First, enhancement factors that applied to undisturbed surface soil ranged from about 0.2 to slightly greater than 1.0, thus indicating that the resuspension factor that applied to the deposited material was somewhat less than the resuspension factor that applied to soil. Second, in cases where surface soil was recently disturbed (e.g., by soil thawing, bulldozer blading, vacuum cleaning, a wildfire, and raking), the enhancement factor that applied to redeposited radioactive material over the first few days following a disturbance ranged from about 2 to more than 8, thus indicating a substantially higher resuspension factor for the redeposited material compared with soil. Finally, in the case of a surface nuclear detonation at NTS, where some of the radioactive material at locations close to ground zero was incorporated in an amorphous silicate glass, referred to as "shot glass," the enhancement factor ranged from about 0.002 to 0.024, thus indicating a much lower resuspension factor for the radioactive material compared with soil. Most of the glass particles were large, with diameters on the order of 1 mm or higher (Lee and Tamura, 1981).

We do not believe that the studies of enhancement factors summarized above indicate that our assumed probability distributions of resuspension factors that apply to all previously deposited fallout in the thermal-pulse or blast-wave region need to be modified. Since the assumed probability distributions were based in large part on data on resuspension of plutonium by mechanical stressors or the wind at NTS and other sites where nuclear weapons were tested [see Table 4-2 and Sehmel (1984; Table 12.7)], these data already incorporate any enhancement factor. Furthermore, large enhancement factors that apply in cases where surface soil was significantly disturbed, especially by human activity, probably are not relevant to resuspension by nuclear detonations at NTS, where most of the land was undisturbed prior to resuspension.

The possibility that the assumed probability distributions of resuspension factors significantly overestimate resuspension of larger fallout particles, as suggested by data on an enhancement factor for shot glass noted above, is potentially important when, as discussed in Section 4.1.3.2.2 below, fallout at NTS consisted mainly of larger particles of diameter greater than 100 μm. This concern could be especially important in the blast-wave region, given that such larger particles usually are not resuspended by the wind (Sehmel, 1980; 1984). However, as indicated by the development of assumptions about the respirable and nonrespirable fractions of resuspended fallout in inhalable form in the following section, the possibility that we have greatly overestimated resuspension of larger fallout particles is unimportant in estimating inhalation dose, essentially because larger particles are assumed not to be inhalable or they would not have remained in the air for a significant period of time even if they were inhalable. That is, an overestimate of resuspension of larger fallout particles is unimportant when those particles do not contribute significantly to inhalation doses.

**4.1.3.2** *Respirable and Nonrespirable Fractions of Resuspended Radionuclides*. In the model currently used to estimate inhalation dose in any resuspension scenario, all resuspended radionuclides are assumed to be inhalable (see Section 3.1). However, it is virtually certain that only a fraction of fallout particles that were resuspended by nuclear detonations at NTS were sufficiently small that they were present in air and could have been inhaled at times shortly after a detonation when exposure in the thermal-pulse or blast-wave region occurred.

As noted previously, quantities of interest to this analysis are resuspension factors that apply to the respirable and nonrespirable, but still inhalable, fractions of radionuclides in fallout that was resuspended in the thermal-pulse or blast-wave region. To estimate those fractions, we first estimate the inhalable fraction of resuspended radionuclides and the respirable fraction of inhalable radionuclides; the product of those fractions gives the respirable fraction of resuspended radionuclides. The nonrespirable fraction of inhalable radionuclides then is estimated from the relationship that the sum of the respirable and nonrespirable fractions of inhalable radionuclides must be unity. The product of that fraction and the inhalable fraction of resuspended radionuclides gives the nonrespirable fraction of resuspended radionuclides. This approach ensures that a proper correlation between the respirable and nonrespirable fractions of

resuspended radionuclides in inhalable form is preserved when all fractions are described by probability distributions to represent their uncertainty; i.e., it ensures that the sum of the respirable and nonrespirable fractions is equal to the inhalable fraction.

Development of probability distributions of the respirable and nonrespirable fractions of resuspended radionuclides in the thermal-pulse and blast-wave regions is described in the following sections. We first discuss the importance of maximum dust loadings in air that can be tolerated while breathing in establishing that most resuspended soil particles in the two regions must have been redeposited on the ground quickly by gravitational settling. The next three sections discuss available data on particle-size distributions of activity in fallout from tower shots at NTS and the use of those data to estimate the fraction of resuspended radionuclides that remained airborne at times of exposure. The last two sections present and discuss the assumed probability distributions of the inhalable and respirable fractions of resuspended radionuclides in the thermal-pulse and blast-wave regions and the nonrespirable fractions of resuspended radionuclides that were derived from those distributions.

**4.1.3.2.1** G*ravitational settling of resuspended material*. In estimating doses from inhalation of radionuclides in fallout that was resuspended in the thermal-pulse or blast-wave region, an important consideration is that the dust loading in air during prolonged exposures had to be less than levels that are intolerable while breathing.[34] Consider, for example, resuspension in the thermal-pulse region. If we assume that the top 1 mm of surface soil was resuspended in that region, the height of the dust cloud was 300 m, and the density of soil was1.5 g $cm^{-3}$, the average dust loading in air would be 5 g $m^{-3}$. An assumption of a greater depth of resuspended surface soil or a lower height of the dust cloud would increase the estimated dust loading. This estimate can be compared with a dust loading of about 0.1 g $m^{-3}$ that was identified by Stewart (1967) as barely tolerable while breathing. The barely tolerable dust loading is nearly two orders of magnitude less than the estimated dust loading in the thermal-pulse region. Therefore, if a

[34] This consideration is based on an assumption that participants who were exposed to resuspended material in the thermal-pulse or blast-wave region at NTS did not wear respiratory protection during their entire period of exposure. Forward observers who were located in the blast-wave region at the time of a detonation may have taken some action to limit inhalation of airborne dust for a short time after detonation (e.g., a few minutes or less), but not for long periods of time.

substantial fraction of surface soil was resuspended in the thermal-pulse region, it is reasonable to conclude that only a small fraction of the resuspended soil could have remained in the air when significant inhalation exposure occurred.

A similar consideration should apply in the blast-wave region. Although a smaller fraction of surface soil presumably was resuspended in that region than in the thermal-pulse region, the dust loading still could have been intolerably high when the lower height of the dust cloud in the blast-wave region is taken into account, especially at locations near the boundary of the thermal-pulse region.

Large reductions in concentrations of resuspended dust to levels that are tolerable while breathing can be obtained by assuming that most material that was resuspended by nuclear detonations consisted of larger particles that fell to Earth quickly by gravitational settling. Consider, for example, gravitational settling of soil particles of diameter 100 μm, which is the largest diameter at which the inhalability of particles has been studied (ICRP, 1994; NCRP, 1997); i.e., particles of diameter greater than 100 μm are assumed to be too large to be inhaled.

Gravitational settling of particles in air occurs under the influence of frictional (viscous) and inertial forces. At a particle diameter of 100 μm, neither force is dominant. In such cases, the settling velocity can be estimated using an approach described by Hinds (1982; Section 3.7 and Table 3.4).[35] For an assumed density of soil particles of 1.5 g $cm^{-3}$ and an assumed dynamic shape factor of 1.57, the estimated settling velocity is 24 cm $s^{-1}$. The dynamic shape factor takes into account that nonspherical particles have lower settling velocities than spherical particles; a dynamic shape factor of 1.57 is a representative value for sand (Hinds, 1982; Table 3.2). At this settling velocity, the time required for a soil particle to fall to Earth from an assumed maximum height of the dust cloud in the thermal-pulse region of 300 m is about 20 minutes. Thus, unless

[35] In this approach, the quantity $C_D Re^2$, where $C_D$ is the coefficient of drag and Re is the Reynolds number, is calculated as $C_D Re^2 = 4d^3 \rho_p \rho_a g / 3\eta^2 \chi$, where $d$ is the particle diameter (i.e., diameter of an equivalent volume sphere for a nonspherical particle) in cm, $\rho_p$ is the particle density in g $cm^{-3}$, $\rho_a$ is the density of air ($1.2 \times 10^{-3}$ g $cm^{-3}$), $g$ is the acceleration due to gravity (981 cm $s^{-2}$), $\eta$ is the viscosity of air ($1.81 \times 10^{-4}$ g $cm^{-1}$ $s^{-1}$) and $\chi$ is the dynamic shape factor; $C_D Re^2$ thus depends on the particle diameter and density but does not depend on the settling velocity. From the calculated value of $C_D Re^2$, the corresponding Reynolds number is obtained from Table 3.4, and the settling velocity, $V$, is calculated from the Reynolds number as $V = (Re)\eta / \rho_a d$. This approach overcomes the problem that although $V$ can be expressed in terms of $C_D$, estimation of $C_D$ requires knowledge of Re, which depends on $V$.

exposure occurred in the thermal-pulse region shortly after a detonation, the largest inhalable soil particles, as well as soil particles that were too large to be inhaled, would not have remained in the air at times of exposure.

In contrast, consider a 10-μm diameter soil particle, which is sufficiently small that the frictional (viscous) force is dominant and Stokes Law can be applied (Hinds, 1982). At that diameter and again assuming a dynamic shape factor of 1.57, the estimated settling velocity is about 0.3 cm $s^{-1}$, and the fall time from a height of 300 m is about 28 hours.

If the maximum height of a dust cloud in the blast-wave region was about one-tenth of the maximum height in the thermal-pulse region, as discussed previously, the maximum fall time for soil particles of diameter 100 or 10 μm would be one-tenth of the maximum fall times in the thermal-pulse region estimated above. Thus, in the blast-wave region, where some forward observers were located at the time of a detonation, the largest inhalable soil particles would have remained airborne for no more than about two minutes, or less if the maximum height of the dust cloud was less than 30 m at locations of exposure, whereas smaller particles remained airborne for a much longer time.

Similar calculations can be performed for fallout particles from tower shots at NTS, which have a density of about 2.7 g $cm^{-3}$ (Miller, 1969). If we assume a dynamic shape factor of 1.3, which is representative of values for clusters of spheres (Hinds, 1982; Table 3.2), the estimated settling velocity of fallout particles of diameter 100 μm is 48 cm $s^{-1}$, and the fall time from a height of 300 m is about 10 minutes. At a particle diameter of 10 μm, the settling velocity is about 0.6 cm $s^{-1}$, and the fall time from a height of 300 m is about 13 hours.

Actual fall times of larger particles may have been somewhat longer than the values estimated above, due to the effects of turbulence in the atmosphere following passage of the blast wave. However, since the highest wind speeds at a given location persisted for only a few seconds and winds thereafter were much weaker (Glasstone and Dolan, 1977), it is not expected that turbulence greatly increased the fall times of larger particles. Furthermore, the estimated fall times of larger particles given above apply to particles that are assumed to fall from the maximum height of the dust cloud, and fall times from that height should have been affected by turbulence to a lesser extent than shorter fall times from lower heights.

**4.1.3.2.2** *Particle-size distributions of activity in fallout*. Fall times of larger fallout particles given in the previous section are relevant when particle-size distributions of activity in fallout are considered. Tower shots produced most of the fallout at NTS to which participants could have been exposed in the thermal-pulse or blast-wave region after a subsequent detonation (Hawthorne, 1979; Dancz and Chehata, 2006).[36] The first tower shot that resulted in significant on-site fallout was Shot EASY in Operation TUMBLER-SNAPPER in 1952. As discussed below, larger particles contained most of the activity in on-site fallout from tower shots; a preponderance of larger particles is expected on the basis of considerations of fractionation of radionuclides in fallout from above-ground detonations (see Section 4.1.2.4).

Data on particle-size distributions of activity in on-site fallout from tower shots at NTS appear to be limited. Data on fallout within about 10 miles of ground zero are of greatest interest to this analysis, because fallout at greater distances did not impact areas where exposure in the thermal-pulse or blast-wave region occurred at subsequent detonations (Dancz and Chehata, 2006; Goetz et al., 1979; Hawthorne, 1979). Data that we are aware of are described below. Data on fallout at distances between 10 and 20 miles also are included to provide additional information that may be useful in interpreting data at closer distances of interest.

Particle diameters in reported particle-size distributions of activity in fallout presumably represent physical diameters as estimated, for example, from sieve analysis of samples. A physical diameter is not the same as an aerodynamic equivalent diameter, which is the diameter of a unit density sphere that has the same settling velocity as the particle of interest and is used in estimating the AMAD of a particle-size distribution for purposes of estimating dose from inhalation of radionuclides (ICRP, 1994; NCRP, 1997). The aerodynamic diameter of a fallout particle of density 2.7 g $cm^{-3}$ (Miller, 1969) with an assumed dynamic shape factor of 1.3 is about 40–50% greater than the physical diameter (Hinds, 1982). However, the distinction

[36] Fallout from surface or underground shots (e.g., Shots SUGAR and UNCLE in Operation BUSTER-JANGLE and Shot ESS in Operation TEAPOT) or airdrop shots (e.g., Shots WASP and WASP PRIME in Operation TEAPOT and Shots WILSON and PRISCILLA in Operation PLUMBBOB) was unimportant, because there was little fallout at NTS or on-site fallout did not significantly impact areas where exposure in the thermal-pulse or blast-wave region occurred after a subsequent detonation. On-site fallout from the few safety shots through Operation PLUMBBOB in 1957 also was unimportant, because those shots did not occur in the same areas as above-ground detonations or they did not impact locations where subsequent exposures of participants occurred.

between the physical and aerodynamic diameter of particles is not important to this report when the objective is to derive effective resuspension factors to the nearest power of 10 only. We also note that: (1) the uncertainty in distributions of physical diameters of fallout particles at NTS is large, as indicated in the following discussions; (2) it is difficult to estimate an AMAD of fallout particles and its uncertainty when data are limited and those quantities depend on particle shapes, which are irregular and variable, as well as their sizes.

Data at Operation TUMBLER-SNAPPER. Particle-size distributions of activity in fallout that was present in surface soil at the end of Operation TUMBLER-SNAPPER in 1952 were reported by Olafson et al. (1953). All data were obtained at locations beyond the boundary of NTS, and only two locations were within 20 miles of a tower shot at that operation. At a distance of 12 miles from Shot HOW, which was detonated at a height of 300 ft with a yield of 14 kt (Hawthorne, 1979), reported percentages of the total activity in the smallest size fractions of fallout were as follows: 0–44 μm, 12%; 44–73 μm, 23%, and 74–149 μm, 13%. At 18 miles from Shots FOX and GEORGE, which were detonated at a height of 300 ft with yields of 11 kt and 15 kt, respectively, percentages in those size fractions were 1.6%, 39%, and 21%. Thus, particles of diameter less than 150 μm contained about half or more of the total activity.

The high percentages of the total activities in the size fraction less than 150 μm noted above may be anomalous, given that the reported percentages in that size fraction at two other locations more than 25 miles from any tower shot in Operation TUMBLER-SNAPPER were 12% and 15% (Olafson et al., 1953). In addition, both measurement locations probably received fallout from the prior underground Shot UNCLE in Operation BUSTER-JANGLE, and the location at 12 miles from Shot HOW probably received fallout from Shot FOX (Hawthorne, 1979). Particle-size distributions of activity in fallout from Shot UNCLE probably did not resemble distributions from tower shots, and Shots HOW and FOX were detonated at different distances from the measurement location closest to Shot HOW. Therefore, it is questionable whether the reported particle-size distributions of activity described above apply to fallout at a known distance from a tower shot.

Data at Operation UPSHOT-KNOTHOLE. Particle-size distributions of activity in fallout from tower Shots NANCY, BADGER, and SIMON in Operation UPSHOT-KNOTHOLE

in 1953 were reported by Rainey et al. (1954). Those shots were detonated at a height of 300 ft with yields of 24 kt at Shot NANCY, 23 kt at Shot BADGER, and 43 kt at Shot SIMON. Reported percentages of the total activities in the smallest size fractions of fallout at distances within 20 miles of those shots are given in Table 4-3. Only the data at the closest distance at each shot apply to on-site fallout. On the basis of these data, we estimate that fallout particles of diameter less than 100 μm, which is the largest diameter at which particles are assumed to be inhalable (ICRP, 1994; NCRP, 1997), contained the following percentages of the total activities in samples closest to ground zero: 51% at Shot NANCY, 9% at Shot BADGER, and 0.3% at Shot SIMON. These estimates were obtained by assuming that particles of diameter less than 100 μm contained one-third of the activity in the 88−125 μm size fraction; i.e., the distribution of activity in that size fraction was assumed to be uniform.

The data at a distance of 3.5 miles from Shot NANCY appear to be anomalous, given that the percentage of the total activity in the size fraction less than 125 μm is much higher than at greater distances. At a distance of about 3 miles from Shot BADGER, the percentage of the total activity in that size fraction also is higher than at greater distances, but differences are not as pronounced as in the data at Shot NANCY. The lower exposure rate at the closest distance at Shot BADGER compared with the three highest exposure rates at greater distances suggests that the closest measurement location was some distance from the centerline of the fallout plume. However, the percentage of the total activity in the size fraction less than 125 μm did not vary greatly at greater distances even though the exposure rate varied by more than a factor of 30. Only the data at Shot SIMON conform to an expectation that the percentage of the total activity in the size fraction less than 125 μm should be smallest at the location closest to ground zero. In addition, in contrast to the data at Shot BADGER, the percentages of the total activities in that size fraction at greater distances were much higher at locations where the exposure rate was relatively low than at locations where the exposure rate was much higher.

Data at Operation TEAPOT. Particle-size distributions of activity in fallout from tower Shots TESLA, TURK, APPLE I, MET, and APPLE II in Operation TEAPOT in 1955 were reported by Baurmash et al. (1958). The heights of detonation and yields were 300 ft and 7 kt at Shot TESLA, 500 ft and 43 kt at Shot TURK, 500 ft and 14 kt at Shot APPLE I, 400 ft and 22 kt

at Shot MET, and 500 ft and 29 kt at Shot APPLE II (Hawthorne, 1979). Reported percentages of the total activities in the smallest size fractions of fallout at distances within 20 miles of those shots are given in Table 4-4. Especially at Shots TESLA, MET, and APPLE II, fallout was collected at several locations at the same distance. These data give information on variations in particle-size distributions at different distances from the centerline of a fallout plume. Only the data at Shot APPLE II apply to on-site fallout. The 0−44 μm size fraction in samples from that shot contained between 0.15% and 2.5% of the total activity, with an average of about 0.9%. By again assuming a uniform distribution of activity in the 88−125 μm size fraction, we estimate that inhalable particles of diameter less than 100 μm in the samples at Shot APPLE II contained between 0.25% and 3.2% of the total activity, with an average of 1.6%.

When compared with the data at other shots in Table 4-4, data at Shot APPLE II conform to an expectation that the percentages of the total activities in the size fraction less than 125 μm were comparable to or less than the percentages in fallout at greater distances. Data at the different shots do not show any evident anomalies.

Data at Operation PLUMBBOB. Data on particle-size distributions of activity in on-site fallout from tower Shots DIABLO and SHASTA in Operation PLUMBBOB in 1957 were reported by Miller (1969). Both shots were detonated at a height of 500 ft with a yield of 17 kt (Hawthorne, 1979). Data on fallout from those shots were obtained at several distances from ground zero between 1.1 and 4.7 miles. These data are more extensive than data on fallout at locations close to tower shots in previous operations.

A particle-size distribution of activity in fallout at a distance of 1.1 miles from Shot DIABLO is shown in Figure 4-1 (Miller, 1969; Figure 8); the separate distributions for large and small particles are discussed later in this section. This figure and the more detailed data on this sample in Table 14 of Miller (1969) indicate that inhalable particles of diameter less than 100 μm contained about 0.7% of the total activity and the 0–44 μm size fraction contained about 0.5%. Similar particle-size distributions of activity in fallout at distances of 2.5 and 4.2 miles from Shot SHASTA are shown in Figures 11 and 13 of Miller (1969) and discussed below.

Fallout from Shot SHASTA was collected at seven locations at distances between 2.2 and 4.7 miles. Reported percentages of the total activities in the smallest size fractions of fallout at

those locations (Miller, 1969; Table 16) are given in Table 4-5. In the five samples with the highest total activities, inhalable particles of diameter less than 100 μm contained between 0.42% and 0.75% of the total activity, with an average of 0.57%. In the two samples with much lower total activities, inhalable particles contained between 2.8% and 6.2% of the total activity. The masses of those samples also were much lower than the masses of the other five samples.

In the seven samples of fallout from Shot SHASTA discussed above, Miller (1969) analyzed particle-size distributions of activity in magnetic and nonmagnetic particles separately. In the five samples with the highest total activities, reported percentages of the total activities in various size fractions of 0−104 μm magnetic fallout particles (Miller, 1969; Table 17) are given in Table 4-6. Data in Table 16 of Miller (1969) indicate that nonmagnetic particles in these five samples had a much higher percentage of their activity in the 0−104 μm size fraction than magnetic particles even though the activity in nonmagnetic particles in that size fraction was substantially less than the activity in magnetic particles. Table 16 of Miller (1969) also gives data on the two samples from Shot SHASTA with the lowest total activities. In these samples, magnetic particles contained 73% and 82% of the total activity in all particle sizes, the percentage of the activity in nonmagnetic particles in the 0−104 μm size fraction was much higher than the percentage of the activity in magnetic particles, and the activity in nonmagnetic particles in that size fraction was much higher than the activity in magnetic particles.

Miller (1969) also analyzed particle-size distributions of activity in small and large particles separately. In the sample at a distance of 1.1 miles from Shot DIABLO for which these activity distributions are shown in Figure 4-1, small particles included all size fractions up to 420 μm and some particles of diameter as large as 1,300 μm, whereas all large particles had diameters greater than 420 μm (Miller, 1969; Table 14). Median diameters in the distributions of activity in small and large particles were 150 and 860 μm, respectively, and small particles contained 3% of the total activity in all particles. In the five samples from Shot SHASTA with the highest total actitivies, small particles included all size fractions in Table 4-5 and some particles of diameter as large as 420, 830, or 1,200 μm, depending on the sample, whereas all large particles had diameters greater than 250, 300, or 420 μm (Miller, 1969; Table 17). Median diameters in the distributions of activity in small particles ranged from 73 to 300 μm, and small

particles contained between 1% and 2.6% of the total activity in all particles, with an average of 2%. Median diameters in the distributions of activity in large particles, which contained an average of 98% of the activity in all particles, ranged from 470 to 900 μm.

Additional data on fallout at a distance of 1 mile from Shot DIABLO were reported by Schuert (1959). However, the particle-size distribution of activity was studied for larger particles (> 200 μm) only; no data were given for smaller particles of interest to our analysis.

Finally, a particle-size distribution of activity in fallout at an off-site location 10 miles from Shot WHITNEY, which was detonated at a height of 500 ft with a yield of 19 kt, was reported by Larson et al. (1966). Data plotted in Figure 3.11 of that report indicate the following percentages of the total activity in the smallest size fractions: 0–44 μm, 6%; 44–88 μm, 1%; and 88–105 μm, <1%. Thus, inhalable particles of diameter less than 100 μm contained about 8% of the total activity.

Particle-Size Distributions of Activity in Off-Site Fallout. Data on particle-size distributions of activity in fallout discussed above were obtained at NTS or at off-site locations within about 20 miles of ground zero of a detonation. Data on particle-size distributions of activity in off-site fallout at locations farther from NTS, such as data reported by Larson et al. (1966) and Cederwall et al. (1990), also could be considered. However, those data are of limited relevance to our analysis when a much higher fraction of the activity in off-site fallout was attached to smaller, inhalable particles, compared with on-site fallout, due primarily to the pronounced decrease in fall times to Earth with increasing particle size.

Data on particle-size distributions of activity in off-site fallout perhaps could be used to estimate an upper bound of the fraction of the activity in on-site fallout that was attached to smaller, inhalable particles. However, given that this fraction is highly variable in the data on fallout at or near NTS, as discussed above and summarized in Tables 4-3 through 4-6, and is also variable in the data at more distant locations, due in part to the variability in distances from ground zero where data were obtained, any such estimate would be difficult to justify. We have not considered data at distances beyond 20 miles in our analysis.

**4.1.3.2.3** *Discussion of data on particle-size distributions*. In principle, it should be possible to predict whether the inhalable fraction in particle-size distributions of activity in

fallout at locations close to ground zero of a detonation was large or small.[37] A key parameter is the scaled height-of-burst, which is the burst height divided by the cube root of the yield (see Section 2.1). When the fireball does not reach the ground and melt a significant amount of soil, the greater the scaled height-of-burst, the more difficult it is for larger soil particles to be sucked into the fireball and, thus, the smaller the size of soil particles that will form part of fallout, along with other materials (e.g., the shot tower and weapon casing). Conversely, the smaller the scaled height-of-burst, the easier it is for larger soil particles to be sucked into the fireball and, thus, the larger the size of soil particles that will form part of fallout. Once fallout particles have formed as the fireball cools, distances from ground zero at which particles of different sizes deposit depend on the stabilization height of the cloud and the wind speeds between the ground surface and the height of the cloud. The scaled height-of-burst also may be an important factor in determining the importance of early fallout of larger particles from the stem.[38]

The principles outlined above suggest that particle-size distributions of activity in fallout at a given distance from ground zero should be similar at detonations with about the same scaled height-of-burst if wind speeds between the ground surface and the stabilization heights of the clouds were not greatly different. Of interest to this analysis is an expectation that, at a given distance close to ground zero (i.e., within the boundary of NTS), the fraction of the total activity in smaller particles often should be about the same. However, data on fallout at distances of about 3–3.5 miles from Shots NANCY, BADGER, and SIMON in Table 4-3 do not conform to this expectation. In those cases, the size fraction less than 125 μm contained widely varying percentages of the total activities even though (1) the scaled heights-of-burst at Shots NANCY and BADGER (104−105 ft) are nearly identical and are not greatly different from the scaled height-of-burst at Shot SIMON (86 ft) and (2) wind speeds up to the stabilization heights of the clouds at those shots varied by less than a factor of 2 (Hawthorne, 1979).

[37] Discussions on the formation of fallout and expected particle-size distributions in fallout are based mainly on personal communications from J. Dancz of Science Applications International Corporation (SAIC); see also Glasstone and Dolan (1977) and Ferlic (1983).

[38] On-site deposition of fallout from the stem at locations close to ground zero probably occurred, for example, at Shot SIMON in Operation UPSHOT-KNOTHOLE (Goetz et al., 1981) and Shot SMOKY in Operation PLUMBBOB (NRC, 2003).

Some differences in particle-size distributions of activity in on-site fallout from the three shots in Table 4-3 could be due to differences in the lateral distance of sampling locations from the centerline of the plumes. The fraction of smaller particles in fallout should be larger near the edges of a plume, where the total activity would be relatively low, than near the center of the plume, where the total activity is the highest, due to the greater diffusion and dispersion of smaller particles during atmospheric transport. Evidence of this effect in fallout at NTS is seen in the data at Shot SHASTA in Table 4-5, where the percentages of the total activities in the size fraction less than 150 μm in the two samples with the lowest activities are at least a factor of 4 higher than the percentages in that size fraction in the five samples with much higher total activities.[39] This effect might be a partial explanation of the high percentage of the total activity in smaller particles in on-site fallout from Shot NANCY in Table 4-3. An inability to separate the 0−5 μm size fraction from the 0−44 μm size fraction in that sample, when the 0−5 μm size fraction was separated in a fallout sample from Shot BADGER, which had a substantially smaller percentage of the total activity in smaller particles, suggests that the total mass and activity were low and, thus, that fallout was not collected near the centerline of the plume where fallout should have consisted mainly of larger particles.[40] However, it is difficult to assess the meaning and importance of differences in the percentages of the total activities in small particles in different fallout samples in any detail when available data are limited and uncertainties in the measurements were not reported.

[39] Clearer evidence of the effect of distance from the centerline of a fallout plume on the fraction of the activity in small particles is seen in the data at distances greater than 10 miles from Shot SIMON in Table 4-3 (but not in the data from Shot BADGER at about the same distances) and Shots TESLA and MET in Table 4-4, as well as the data at a distance of 35 miles from Shot BOLTZMANN in Operation PLUMBBOB (Larson et al., 1966; Figure 3.12).

[40] Another factor that could have affected the particle-size distribution of activity in the sample of on-site fallout from Shot NANCY is the meandering of the plume at times shortly after detonation, which probably delayed the arrival time of fallout at the location 3.5 miles from ground zero compared with the arrival times of fallout from the other shots in Table 4-3 at about 3 miles (J. Dancz, SAIC, personal communication). A delay in the arrival time of fallout could have significantly increased the fraction of smaller particles (Ferlic, 1983). This effect is shown, for example, by an increase in the percentage of the total beta activity in the 0–44 μm size fraction in fallout from Shot SMOKY in Operation PLUMBBOB as the arrival time increased from 1 to 15 hours (Larson et al., 1966; Figure 3.14 and Table 3.2).

Given the kinds of inconsistencies noted above, it is difficult to estimate particle-size distributions of activity in fallout on the basis of principles of fallout formation. Rather, we have relied on available data and attempted to take the variability in the data into account.

**4.1.3.2.4** *Implications and use of available data*. The considerations of a maximum dust loading in air that is barely tolerable while breathing, fall times of fallout particles of different sizes in dust clouds produced in nuclear detonations, and data on particle-size distributions of activity in on-site fallout from tower shots at NTS described above indicate that, on average, only a small fraction of the activity of radionuclides in fallout that was resuspended in the thermal-pulse or blast-wave region could have been inhaled by participants; i.e., most of the resuspended fallout must have fallen to Earth before significant inhalation exposure could have occurred. This conclusion applies even in cases of exposure of participants who were present in the blast-wave region at the time of a detonation, because larger particles remained in the air for only a short time. For example, the estimated fall time of a 100-μm diameter fallout particle that was resuspended to a height of 10 m is about 20 s (see Section 4.1.3.2.1).

A confounding factor, however, is the variable data on particle-size distributions of activity in on-site fallout, as discussed in Section 4.1.3.2.2. Data on some samples indicate that smaller particles that could have remained in the air to be inhaled by participants contained a substantial fraction of the total activity.

We are unaware of any published information on particle-size distributions of airborne activity in fallout that was resuspended by nuclear detonations at NTS. Therefore, the fraction of the activity in resuspended fallout that could have been inhaled when effects of particle size on potential exposures are considered is highly uncertain.

In the absence of data, we use assumptions described in the following three sections to estimate upper and lower bounds of the fractions of the activity of resuspended radionuclides in respirable or nonrespirable form that could have been inhaled by participants. These estimates are assumed to apply throughout the thermal-pulse and blast-wave regions. As noted previously, respirable and nonrespirable fractions of resuspended radionuclides in inhalable form are estimated on the basis of estimates of the inhalable fraction of resuspended radionuclides and the respirable fraction of inhalable radionuclides. Respirable particles are assumed to have a

diameter (AMAD) of about 10 μm or less (ICRP, 1994), and we assume that inhalable particles have a diameter less than 100 μm (ICRP, 1994; NCRP, 1997). Since fallout particles of diameter greater than 100 μm have fall times to Earth from a height of 300 m (the assumed maximum height of resuspended material in the thermal-pulse region) of about 10 minutes or less and fall times in the blast-wave region should not exceed 1 minute if the maximum height of resuspended material in that region was a few tens of meters (see Section 4.1.3.2.1), exposure times and inhalation doses in the thermal-pulse and blast-wave regions would be unimportant even if such particles were inhalable.

In using available data on particle-size distributions of activity in fallout at NTS, rather than modeling, to estimate the inhalable fraction of resuspended radionuclides and the respirable and nonrespirable fractions of resuspended radionuclides in inhalable form, it is important to recognize limitations in the data. At many shots that produced fallout that could have been resuspended by subsequent detonations, data either were not obtained or were not known to us. In addition, data that were known to us were obtained at very few locations. This is an important consideration when participants often were exposed to resuspended fallout at various distances and directions from ground zero of a previous shot as they moved through the fallout field from that shot (e.g., in carrying out a maneuver or moving toward a display area), particle-size distributions in fallout from a given prior shot presumably depended on the distance from ground zero and the lateral distance from the centerline of the plume, and exposure to fallout from more than one previous shot with ground zeros at different locations occurred in some cases. Thus, available data on particle-size distributions are not definitive, and estimation of credibility intervals of the inhalable and respirable fractions of fallout that was resuspended by nuclear detonations necessarily involves a high degree of subjective judgment.

**4.1.3.2.5** *Estimation of inhalable fraction.* Given the limited data on particle-size distributions of activity in fallout at NTS, we believe that upper and lower bounds (credibility limits) of the inhalable fraction of radionuclides in fallout that was resuspended by nuclear detonations should be specified to powers of 10 only, as was done in defining the probability distributions of resuspension factors that apply to all fallout (see Section 4.1.3.1). We develop the assumed credibility limits of the inhalable fraction as described below.

A lower credibility limit of the inhalable fraction of resuspended radionuclides is estimated on the basis of two assumptions: (1) all inhalable radionuclides were attached to particles of diameter about 44 μm or less, and (2) particle-size distributions of activity in resuspended fallout were the same as the distributions in on-site fallout from tower shots at locations of higher total activity where the smallest particles had the lowest percentages of the total activity. A maximum diameter of about 44 μm often defines the smallest size fraction that was used in specifying particle-size distributions of activity (see Tables 4-3 through 4-6).

An assumption that the maximum particle size of inhalable material was about 44 μm for the purpose of estimating a lower credibility limit of the inhalable fraction of resuspended radionuclides, rather than 100 μm (ICRP, 1994; NCRP, 1997) as discussed previously, is supported by the following argument. First, if the maximum height of resuspended material in the thermal-pulse region is assumed to be 300 m, fallout particles of diameter greater than 44 μm in that region have estimated fall times to Earth of about 40 minutes or less.[41] Since participants (i.e., forward observers or maneuver troops) did not enter the thermal-pulse region for some time after a detonation (perhaps a few tens of minutes or more), any exposures to inhalable particles of diameter greater than 44 μm that might have occurred should have been of short duration. Second, since the height of resuspended material in the blast-wave region was less than in the thermal-pulse region, fall times would be reduced in proportion to reductions in the height of the cloud. The photograph in Figure 2-1 and other similar photographs (AFLML, 1951) indicate that the maximum height of resuspended material in the blast-wave region was no more than a few tens of meters, and estimated fall times of fallout particles of diameter greater than 44 μm from such heights are less than 5 minutes. Consequently, inhalation of those particles should not have occurred when participants entered the blast-wave region after a detonation, and inhalation of those particles should not have been important when forward observers were located in the blast-

[41] Fallout particles of diameter 44 μm are sufficiently small that the Reynolds number (Re) is substantially less than 1.0 and, therefore, frictional (viscous) forces are dominant and the settling velocity, $V$, can be calculated using Stokes Law as $V = \rho_p d^2 g / 18\eta\chi$ (Hinds, 1982), where $\rho_p$ is the particle density (2.7 g cm$^{-3}$), $d$ is the particle diameter in cm, $g$ is the acceleration due to gravity (981 cm s$^{-2}$), $\eta$ is the viscosity of air ($1.81 \times 10^{-4}$ g cm$^{-1}$ s$^{-1}$), and $\chi$ is the dynamic shape factor, which is assumed to be 1.3 for fallout particles (see Section 4.1.3.2.1).

wave region at the time of a detonation, due to the short exposure time before such particles fell to Earth.[42]

On the basis of the assumptions described above, we assume that a lower credibility limit ($5^{th}$ percentile) of the inhalable fraction of radionuclides in resuspended fallout is 0.001 (0.1%). This credibility limit represents the lowest percentages of the total activities in particles of diameter less than 44 μm at locations of relatively high total activity in on-site fallout from Shots APPLE II and SHASTA (see Tables 4-4 and 4-5). An estimate of 0.01% in a sample at Shot SIMON (see Table 4-3) was excluded, mainly on the grounds that the exposure rate at the location of that sample was not reported and only one sample of on-site fallout from that shot was analyzed. In addition, the estimate of 0.01% is an order of magnitude lower than any other estimate in the data we reviewed and, thus, may be anomalous. By assuming an unbounded probability distribution, as described later in this section, we also have assumed that there is a small probability that the inhalable fraction of radionuclides in resuspended fallout was substantially less than 0.001.

We then assume that an upper credibility limit ($95^{th}$ percentile) of the inhalable fraction of radionuclides in resuspended fallout is 0.1 (10%). This assumption is based mainly on the reported percentages of the total activities in particles of diameter less than 100 μm in on-site

[42] As an example, we consider an extreme case in which the concentration of plutonium on the ground surface is assumed to be $3 \times 10^3$ nCi $m^{-2}$, the resuspension factor that applies to all fallout in the blast-wave region is assumed to be $10^{-3}$ $m^{-1}$, all resuspended plutonium is assumed to be inhalable, and the breathing rate is 2 $m^3$ $h^{-1}$. The assumed concentration of plutonium represents the highest concentration over a substantial area at NTS after the period of atmospheric testing (McArthur, 1991; Figure 2) and, thus, should overestimate concentrations at locations of exposure to fallout that was resuspended by nuclear detonations; the assumed resuspension factor is the upper 95% credibility limit in the blast-wave region developed in Section 4.1.3.1.2; the assumption that all resuspended plutonium is inhalable should overestimate airborne concentrations of inhalable plutonium in regions of high fallout depositions at NTS, where most fallout particles should have been too large to be inhaled; and the assumed breathing rate applies under conditions of moderately strenuous activity (EPA, 1997). Using these assumptions and current dose coefficients for ingestion (ICRP, 2002) that are adjusted by the fraction of inhaled material that would be swallowed (see Section 3.1), which apply when inhaled material is nonrespirable, the highest equivalent dose to any organ or tissue from a 5-minute exposure to airborne plutonium is about 4 mrem to bone surfaces. Such a low dose under conditions that should greatly overestimate actual exposures shows that doses from intakes of larger inhalable particles with short fall times to Earth must have been very low. This conclusion also applies in the thermal-pulse region where the resuspension factor that applies to all fallout on the ground surface is assumed to be an order of magnitude higher and exposure times may have been longer (a few tens of minutes at most).

fallout from Shot BADGER (see Table 4-3) and fallout at a distance of 10 miles from Shot WHITNEY noted in Section 4.1.3.2.2. The assumed upper credibility limit is more than an order of magnitude higher than the percentages of the total activities in particles of diameter less than 44 μm in the five samples with the highest total activity in fallout from Shot SHASTA (see Table 4-5) and the average percentage of the total activity in that size fraction in fallout from Shot APPLE II (see Table 4-4). In estimating an upper credibility limit of the inhalable fraction on the basis of percentages of the total activities in particles of diameter up to 100 μm, we have assumed implicitly that the particle-size distributions of activity in resuspended fallout included a substantially higher fraction of smaller particles than the distributions of resuspended soil particles, because the dust loading in air presumably was intolerable while breathing unless most of the resuspended soil consisted of larger particles that fell to Earth within a short time (see Section 4.1.3.2.1). An estimate of about 50% in a sample of on-site fallout from Shot NANCY (see Table 4-3) was excluded on the grounds that the high percentage of the total activity in small particles in that sample appears to be anomalous when compared with estimates of less than 10% in two samples at greater distances from ground zero (see Section 4.1.3.2.2). By assuming an unbounded probability distribution, as described below, we also have assumed that there is a small probability that the inhalable fraction of radionuclides in resuspended fallout was substantially greater than 0.1.

We also believe that intermediate values of the inhalable fraction were more likely than the upper and lower credibility limits developed above. Therefore, we assume that the inhalable fraction of radionuclides in fallout that was resuspended in the thermal-pulse or blast-wave region is represented by a lognormal probability distribution with a 90% credibility interval between 0.001 and 0.1.[43] The median of this distribution of 0.01 (1%) does not differ greatly from an average fraction of the total activity in particles of diameter less than 44 μm in on-site fallout, as estimated from data in Tables 4-3, 4-4, and 4-5 but excluding data at Shot NANCY in

[43] The assumed distribution assigns a small probability to an inhalable fraction greater than 1.0, which is not possible. However, that probability is less than 0.05% and, thus, is very small. The small probability of selecting a value greater than 1.0 by random sampling does not have a significant effect on an analysis of uncertainty in estimates of inhalation dose, and no correction is made to account for impossible values.

Table 4-3. As noted previously, particles in 0–44 μm size fraction are expected to comprise most of the airborne materials that could have been inhaled in the thermal-pulse and blast-wave regions. The median of 0.01 also is consistent with an estimate obtained by assuming that about half of the activity in small particles with a median diameter of 75−300 μm in fallout from Shot SHASTA (Miller, 1969), but none of the activity in large particles, remained in the air for a sufficient time to be inhaled.

The probability distribution of the inhalable fraction of resuspended radionuclides developed above is intended to apply at any location where significant resuspension by a nuclear detonation at NTS occurred. In a more refined analysis, a smaller inhalable fraction could be assumed in regions of higher concentrations of fallout, where larger particles should have contained more of the total activity, and a larger inhalable fraction could be assumed in regions of lower concentrations, where smaller particles should have contained more of the total activity. These inhalable fractions would have a smaller uncertainty than the single inhalable fraction that is assumed to apply at all locations in the thermal-pulse and blast-wave regions. However, it is difficult to define regions of higher and lower concentrations of fallout when a continuum of concentrations occurred in fallout from any shot, and we do not believe that the available data on particle-size distributions are sufficient to justify such an approach even if those regions could be defined in a reasonable manner.

Data in Tables 4-3, 4-4, and 4-5 indicate that the 95$^{th}$ percentile of the assumed probability distribution of the inhalable fraction of resuspended radionuclides of 0.1 is somewhat higher than needed to give a credible upper bound in regions of higher concentrations of fallout, where inhalation doses would be the highest—i.e., a credible upper bound in those regions could be somewhat less than 0.1. However, as noted previously, we believe that specifying an upper 95% credibility limit more precisely than to the nearest power of 10 is difficult to justify, given the limited data on particle-size distributions of activity in fallout at NTS and the uncertainty in assuming that particle-size distributions of activity in resuspended fallout were the same.

**4.1.3.2.6** *Estimation of respirable fraction*. Data that can be used to estimate the respirable fraction of the total activity of radionuclides in fallout that was resuspended by a nuclear detonation (i.e., the activity in particles of diameter about 10 μm or less) are more limited

than data on the inhalable fraction discussed in the previous section. However, the respirable fraction must have been less than the inhalable fraction when respirable particles are included in the larger size range of inhalable particles. On the basis of an argument in the previous section that most of the inhalable material in the thermal-pulse and blast-wave regions had a diameter of about 44 μm or less, we assume that the respirable fraction of resuspended radionuclides in inhalable form can be represented by the fraction of the activity in the 0−44 μm size fraction that occurred in particles of diameter up to 10 μm.

Data on particle-size distributions of activity in on-site fallout from Shots BADGER, APPLE II, and SHASTA in Tables 4-3, 4-4, and 4-6, respectively, indicate that the respirable fraction of the 0–44 μm size fraction could have been as low as about 0.01 and as high as 1.0. The lowest estimate is based on data from a sample of magnetic fallout particles at a distance of 2.5 miles from ground zero at Shot SHASTA; an estimate of about 0.06 is obtained from data on another sample at a distance of 4.7 miles at that shot. The highest estimate is based on data from the sample at Shot APPLE II that had the lowest total activity. If the particle-size distribution of activity in all 5−20 μm size fractions at Shot APPLE II is assumed to be uniform, the average for all samples at that shot is about 0.7. The data at Shot BADGER give an estimate of about 0.2 if the particle-size distribution of activity in the 5−44 μm size fraction also is assumed to be uniform. An additional estimate of about 0.4 is obtained from the particle-size distribution of activity in small particles in a sample from Shot DIABLO (Miller, 1969; Table 14).

On the basis of the limited data summarized above, we assume that the respirable fraction of resuspended fallout particles of diameter 0–44 μm could range from 0.01 to 1.0. We also assume that the most likely value is 0.3, which is an estimate obtained by averaging the single estimates at Shots BADGER and DIABLO and averages of the multiple estimates at Shots APPLE II and SHASTA. We represent the respirable fraction of the 0–44 μm size fraction by a log-triangular distribution with a minimum at ($ln$ 0.01) = −4.6, mode at ($ln$ 0.3) = −1.2, and maximum at ($ln$ 1.0) = 0. The median of this distribution is 0.17, the mean is 0.22, and the 90% credibility interval ranges from 0.024 to 0.59.

A bounded probability distribution, rather than an unbounded distribution (e.g., lognormal), is chosen to represent the respirable fraction of inhalable radionuclides because

values greater than 1.0 are not possible, values well within an order of magnitude of the highest possible value appear to be the most likely, and a credible lower bound is much less than the upper bound. A lognormal distribution would not adequately represent the assumed upper and lower bounds and most likely value. A log-triangular, rather than a triangular, distribution is assumed on the grounds that log-transformed distributions are preferable when credible values could vary by more than an order of magnitude (NCRP, 1996). A log-uniform distribution is inappropriate when intermediate values appear to be much more likely than extreme values.

The respirable fraction of radionuclides in fallout that was resuspended by a nuclear detonation at NTS is represented by a probability distribution that is obtained by combining the probability distribution of the inhalable fraction of resuspended radionuclides developed in the previous section with the probability distribution of the respirable fraction of inhalable radionuclides given above. The resulting probability distribution of the respirable fraction of resuspended radionuclides has a median at $1.5 \times 10^{-3}$ and 90% credibility interval between $8.2 \times 10^{-5}$ and $2.3 \times 10^{-2}$. The uncertainty in the inhalable fraction of resuspended radionuclides contributes two-thirds of the total uncertainty.

The assumed probability distribution of the respirable fraction of resuspended radionuclides may tend to overestimate actual values. If the inhalable fraction included particles of diameter substantially greater than 44 μm, the fraction of the activity in the inhalable size fraction that occurred in particles of diameter up to 10 μm would be overestimated. In addition, as noted in Section 4.1.3.2.2, reported diameters of fallout particles presumably are physical diameters that are less than the corresponding aerodynamic equivalent diameters. Thus, by assuming that fallout particles of physical diameter up to 10 μm are respirable, the respirable fraction should include some nonrespirable particles with an AMAD greater than 10 μm. However, we do not expect that a possible overestimation of the respirable fraction of resuspended radionuclides would be significant compared with the assumed uncertainty.

**4.1.3.2.7** *Estimation of nonrespirable fraction*. The nonrespirable fraction of radionuclides in inhalable form (i.e., the nonrespirable fraction of the 0−44 μm size fraction of resuspended radionuclides) is obtained from the relationship that the sum of the nonrespirable and respirable fractions of inhalable radionuclides is unity. The resulting probability distribution

of the nonrespirable fraction of inhalable radionuclides has a median at 0.83 and 90% credibility interval between 0.41 and 0.98. The much smaller uncertainty in this fraction compared with the uncertainty in the respirable fraction of inhalable radionuclides is a consequence of an assumption of a high probability that the respirable fraction was much less than 1.0.

By combining the probability distribution of the nonrespirable fraction of inhalable radionuclides given above with the probability distribution of the inhalable fraction of resuspended radionuclides that was developed in Section 4.1.3.2.5, the resulting probability distribution of the nonrespirable fraction of resuspended radionuclides has a median at $7.6 \times 10^{-3}$ and 90% credibility interval between $7.0 \times 10^{-4}$ and $8.0 \times 10^{-2}$. As expected, this probability distribution is not greatly different from the assumed probability distribution of the inhalable fraction of resuspended radionuclides. The uncertainty in the inhalable fraction of resuspended radionuclides contributes 97% of the total uncertainty.

The assumed probability distribution of the nonrespirable fraction of resuspended radionuclides may tend to underestimate actual values if the respirable fraction tends to be overestimated, as discussed in the previous section. However, any such tendency would be unimportant compared with the assumed uncertainty in the nonrespirable fraction when that fraction is much greater than the respirable fraction. We also note that the difference between the physical diameter of a fallout particle and the corresponding aerodynamic equivalent diameter, as discussed in Section 4.1.3.2.2, is unimportant in estimating the nonrespirable fraction, because the dose from inhalation of nonrespirable particles, which are either expelled or swallowed, is independent of particle size.

We also considered the possibility that the respirable and nonrespirable fractions of radionuclides in inhalable form might be correlated to some degree with the inhalable fraction of resuspended radionuclides. This correlation and its potential effects on our analysis of uncertainty are considered in Section 4.2.5.

**4.1.3.3** *Summary of Uncertainties in Resuspension Factors*. Overall uncertainties in resuspension factors that are used to estimate activity concentrations of radionuclides in respirable or nonrespirable form that could have been inhaled by military participants in the thermal-pulse and blast-wave regions of nuclear detonations at NTS relative to the

concentrations in fallout on the ground surface are obtained by combining estimated uncertainties in (1) the resuspension factor that applies to all fallout, (2) the inhalable fraction of resuspended radionuclides, and (3) the respirable or nonrespirable fraction of resuspended radionuclides in inhalable form. Estimated uncertainties in the three parameters that were developed in Sections 4.1.3.1 and 4.1.3.2 are summarized in Table 4-7. We obtain the following medians and 90% credibility intervals of probability distributions of resuspension factors that apply to radionuclides in respirable or nonrespirable form in the two regions:

- Radionuclides in respirable form in thermal-pulse region – Median resuspension factor at $1 \times 10^{-6}$ $m^{-1}$ and 90% credibility interval between $4 \times 10^{-8}$ and $6 \times 10^{-5}$ $m^{-1}$;
- Inhalable radionuclides in nonrespirable form in thermal-pulse region – Median resuspension factor at $8 \times 10^{-6}$ $m^{-1}$ and 90% credibility interval between $3 \times 10^{-7}$ and $2 \times 10^{-4}$ $m^{-1}$;
- Radionuclides in respirable form in blast-wave region – Median resuspension factor at $1 \times 10^{-8}$ $m^{-1}$ and 90% credibility interval between $7 \times 10^{-11}$ and $3 \times 10^{-6}$ $m^{-1}$;
- Inhalable radionuclides in nonrespirable form in blast-wave region – Median resuspension factor at $8 \times 10^{-8}$ $m^{-1}$ and 90% credibility interval between $4 \times 10^{-10}$ and $1 \times 10^{-5}$ $m^{-1}$;

These results are given to one significant figure only, to reflect the large uncertaintis and the subjective nature of assumed probability distributions of each parameter. We also reiterate that resuspension factors in the blast-wave region are intended to be averages of values that are expected to decrease with increasing distance from ground zero (see Section 4.1.3.1.2).

In the thermal-pulse region, where the assumed uncertainties in the resuspension factor that applies to all radionuclides and the inhalable fraction of resuspended radionuclides both are a factor of 10, each of those uncertainties contributes 40% and 49% of the total uncertainties in the resuspension factors that apply to radionuclides in respirable and nonrespirable form, respectively. The uncertainty in the respirable fraction of inhalable radionuclides contributes the remaining uncertainties of 20% and 2%, respectively. In the blast-wave region, the assumed

uncertainty of a factor of 100 in the resuspension factor that applies to all radionuclides contributes 74% and 80% of the total uncertainties in the resuspension factors that apply to radionuclides in respirable and nonrespirable form, respectively. For radionuclides in respirable form, the assumed uncertainties in the inhalable fraction of resuspended radionuclides and the respirable fraction of inhalable radionuclides contribute 18% and 9% of the total uncertainty, respectively, and for radionuclides in nonrespirable form, those contributions are 19% and 0.6%.

The probability distributions of resuspension factors summarized above are well represented by lognormal distributions with the indicated 90% credibility intervals. This is an expected result when the two parameters that contribute most of the total uncertainties are assumed to be lognormally distributed. In the thermal-pulse region, GSDs of lognormal probability distributions with the indicated 90% credibility intervals are about 9.2 and 7.2 for radionuclides in respirable and nonrespirable form, respectively. In the blast-wave region, the corresponding GSDs are about 26 and 22.

### **4.1.4** *Breathing Rate*

A breathing rate of 1.2 $m^3\ h^{-1}$ is assumed in most dose reconstructions (Egbert et al., 1985; Raine et al., 2007). The assumed breathing rate is intended to be somewhat higher than a typical value during light activity.

If a breathing rate during light activity applies to participants in the thermal-pulse or blast-wave region shortly after a nuclear detonation, an analysis by the U.S. Environmental Protection Agency (EPA, 1997) indicates that the 90% credibility interval in adults ranges from 0.6 to 1.4 $m^3\ h^{-1}$. We assume that the upper credibility limit should be increased to 2 $m^3\ h^{-1}$ on the grounds that some activities, such as marching in full battle gear during post-shot maneuvers, were more strenuous than normal light activities. The excitement of being near ground zero shortly after a nuclear detonation also could have resulted in increased breathing rates.

On the basis of the considerations described above, we assume that the uncertainty in the breathing rate is represented by a lognormal probability distribution with a 90% credibility

interval between 0.6 and 2.0 $m^3\ h^{-1}$. The median breathing rate of 1.1 $m^3\ h^{-1}$ is slightly less than the value assumed in most dose reconstructions. The GSD of this distribution is about 1.4.

### **4.1.5** *Dose Coefficients for Inhalation of Radionuclides*

This section considers uncertainties in dose coefficients for inhalation of radionuclides that are used in dose reconstructions. Assumptions about particle sizes of inhaled materials that have been used in calculating dose coefficients for inhalation (Egbert et al., 1985; Raine et al., 2007) are described in Section 3.1. Doses from inhalation of nonrespirable particles can be estimated using dose coefficients for ingestion that are adjusted to account for the fraction of the inhaled material that is assumed to be swallowed.

Dose coefficients for inhalation or ingestion that are used in most dose reconstructions are 50-year committed doses—i.e., doses delivered over a period of 50 years following an acute intake of radionuclides—that are assigned to the year of intake.[44] For short-lived radionuclides or longer-lived radionuclides with short retention half-times in the body (e.g., $^{137}Cs$), 50-year committed doses essentially are received within the first year after an intake. For long-lived radionuclides with long retention half-times in the body (e.g., plutonium), 50-year committed doses to many organs or tissues are protracted over time at a nearly constant rate, and the dose received in any year is approximately 1/50th of the 50-year committed dose.

**4.1.5.1** *Sources of Uncertainty in Dosimetric and Biokinetic Models*. Dosimetric models that are used to calculate dose coefficients for inhalation or ingestion give estimates of absorbed dose to specific target organs or tissues per decay of radionuclides in specific source organs or tissues, which are sites of deposition or transit in the body. Uncertainty in dosimetric models arises mainly from uncertainties in the masses of target organs or tissues (e.g., the thyroid), the

[44] An exception occurs when leukemia is the cancer type of concern and a dose reconstruction is required. In such cases, doses to red bone marrow that are received in each year following an intake in a given year are calculated (DTRA, 2007), because use of 50-year committed doses that are assigned to the year of intake could result in underestimates of upper 99% credibility limits of the probability of causation of leukemia (Kocher and Apostoaei, 2007) in some cases. Such calculations are rarely required, however, because Department of Veterans Affairs (DVA) regulations in 38 CFR 3.309 specify that most types of leukemia are presumptive diseases, and service connection usually is granted without regard for a participant's dose.

spatial relationships between sites of deposition or transit and other target organs or tissues, and calculations of radiation transport between a source and target. These uncertainties are unimportant in some cases, such as when a radionuclide emits mainly high-energy photons or is distributed relatively uniformly in body tissues (e.g., $^{137}$Cs, $^{14}$C). However, they can be important in other cases, such as in estimating dose to red bone marrow from alpha-emitting radionuclides (e.g., plutonium) deposited in the skeleton or dose to walls of the stomach and colon from ingested alpha emitters in contents of the GI tract (Eckerman et al., 1999).

Biokinetic models describe the behavior of inhaled or ingested radionuclides in the body over time after an intake and are used to estimate residence half-times in specific organs or tissues. By taking known half-lives of radionuclides into account, biokinetic models essentially give estimates of the number of decays of radionuclides in specific source organs or tissues over a specified time after intake (e.g., 50 years) per unit activity intake. Uncertainty in biokinetic models arises mainly from uncertainties in absorption of radionuclides into blood from the lungs or GI tract, the fraction of the absorbed activity that is deposited in specific organs or tissues, and the biological half-times for retention at each site of deposition. The biokinetic behavior of many radionuclides depends on their chemical form, and that dependence can be an important source of uncertainty in biokinetic models when chemical forms of radionuclides are unknown or the behavior of known chemical forms has not been studied in humans or animals. Uncertainties in biokinetic models can be small (e.g., a factor of about 3 or less) in some cases, such as intakes of $^{137}$Cs or $^{131}$I by any route, but they can be large (e.g., a factor of 10 or more) in other cases, such as ingestion of plutonium or other radionuclides for which the uncertainty in absorption into blood from the GI tract is large.

Another possible source of uncertainty in dose coefficients for inhalation is an uncertainty in the distribution of particle sizes of inhaled material. This distribution can affect the fraction of inhaled material that is deposited in various regions of the respiratory tract. Dose coefficients for inhalation of particles with an AMAD of 1 μm or greater usually are calculated by assuming a lognormal distribution of particle sizes with a GSD of 2.5 (ICRP, 1994).[45] The

[45] For a given GSD, the 95$^{th}$ and 5$^{th}$ percentiles of a lognormal distribution are a factor of GSD$^{1.645}$ above and below the geometric mean (median), respectively.

GSD of particle-size distributions of inhalable material that was resuspended by nuclear detonations at NTS could be substantially different. However, calculations by Huston (1995) suggest that any such differences are unimportant. In cases of inhalation of respirable particles with an AMAD of about 10 μm or less, which are deposited to a significant extent in the bronchial and pulmonary regions, those calculations indicate that an increase in the GSD of the particle-size distribution from 2 to 4 would change the uncertainty in a dose coefficient for the lung by less than a factor of 2. When larger, nonrespirable particles, which are deposited almost entirely in the nose, throat, and mouth, are inhaled, the deposition fraction and subsequent transfer to the GI tract are independent of particle size, as noted in Section 4.1.3.2.7. On the basis of these calculations, we assume that uncertainties in dose coefficients for inhalation that arise from an uncertainty in the distribution of particle sizes of inhaled material are negligible compared with uncertainties in dosimetric and biokinetic models.[46]

**4.1.5.2** *Overview of Approach to Evaluating Uncertainty in Dose Coefficients*. A rigorous analysis of uncertainty in dose coefficients for inhalation or ingestion of radionuclides in fallout would be a difficult undertaking. Such an analysis would require a consideration of uncertainties in dose coefficients for essentially all organs or tissues, including organs or tissues (e.g., the prostate) at minor sites of deposition, which often are of concern in dose reconstructions when cancers at those sites are nonpresumptive diseases, and for many radionuclides.[47] However, uncertainties appear to be well characterized for only a few combinations of radionuclide and organ or tissue, and those organs or tissues usually are not of concern in dose reconstructions when cancers at those sites are presumptive diseases.

[46] We also note that 10 μm is a reasonable dividing line between monodisperse particles (particles of the same diameter) that are respirable and deposit to a significant extent in the deep lung and particles that are nonrespirable (ICRP, 1994). These considerations, along with the importance of subjective judgment in estimating uncertainties in resuspension factors and the inhalable and respirable fractions of resuspended radionuclides, provide some justification for the lack of rigor in using the term "diameter" to describe particle sizes in this report (see also Section 4.1.3.2.2). When the objective of our analysis is to derive effective resuspension factors to the nearest power of 10 only, such rigor is not necessary.

[47] Although cancers in many organs or tissues are presumptive diseases, as specified in DVA regulations in 38 CFR 3.309, and a dose reconstruction usually is not required in adjudicating claims for compensation, a dose reconstruction is required when an individual's participation in the atmospheric nuclear-weapons testing program is not adequately established or a claim is intended to apply to a time period prior to the time when an individual's cancer was declared to be a presumptive disease.

Another confounding factor in evaluating uncertainties in dose coefficients is that biokinetic models recommended by ICRP may be based on studies of chemical and physical forms of radionuclides that differ substantially from chemical and physical forms in fallout. For example, data in humans (LeRoy et al., 1966) indicate that the GI-tract absorption fraction of strontium and cesium in fallout particles is less than ICRP's recommended values, and animal studies also indicate that GI-tract absorption of many (but not all) radionuclides in fallout particles is unusually low.[48] However, there also are data which indicate that an appreciable fraction of cerium in fallout is more soluble than oxide forms (NCRP, 1978) and, thus, that absorption in the GI tract and lung may be higher than recommended by ICRP. Doses to walls of the GI tract from ingestion of plutonium in larger fallout particles also could be overestimated substantially when ICRP's dosimetric model for the GI tract (ICRP, 1979) does not take into account that plutonium should be distributed in the volume of insoluble fallout particles and, thus, that much of the emitted alpha energy should be absorbed in the particles.

In principle, it is desirable to develop estimates of uncertainty in dose coefficients for inhalation or ingestion that apply to specific radionuclides, or groups of radionuclides, and to specific organs or tissues, or groups of organs or tissues, for which uncertainties are expected to be similar, because studies discussed in the following section indicate that uncertainties can vary greatly depending on the radionuclide and organ or tissue of concern. However, even if available information on uncertainties in dose coefficients were adequate to pursue such an approach, we believe that it would be impractical to use several different estimates of uncertainty in dose coefficients in this analysis, or in dose reconstructions for military participants. The number of substantially different mixtures of radionuclides to which participants could have been exposed is potentially large when exposure to resuspended fallout at many times after detonations, ranging from hours to years, could have occurred, and it is not clear how a presumably small number of discrete estimates of uncertainty should be applied to what is essentially a continuum of mixtures of radionuclides. An assumption of different uncertainties in dose coefficients for different combinations of radionuclides and organs or tissues of concern could result in estimates of effective resuspension factors in the thermal-pulse and blast-wave

[48] R.W. Leggett, Oak Ridge National Laboratory, personal communication.

regions to be used in dose reconstructions that depend on the organ or tissue and the times since previous depositions of fallout when exposure occurred. Such an approach would be incompatible with the approach currently used in dose reconstructions in other resuspension scenarios, in which a single adjustment factor, which is intended to account for uncertainty, is applied to point estimates of inhalation dose to obtain credible upper bounds in all cases (DTRA, 2007; Case et al., 2008). Use of uncertainties in dose coefficients that depend on the particular mixture of radionuclides and the organ or tissue of concern probably can be justified only if dose reconstructions were performed by taking into account uncertainties in all parameters (i.e., by using a fully probabilistic uncertainty analysis).

On the basis of considerations discussed above, we believe that the only practical approach for purposes of this analysis is to develop estimates of uncertainty in dose coefficients for inhalation or ingestion (i.e., inhalation of larger, nonrespirable particles) that are intended to apply to all organs or tissues of possible concern. As in assessing the effects of fractionation of radionuclides in fallout (see Section 4.1.2.4), plutonium is considered separately from fission and activation products on the grounds that there are sources of uncertainty in internal dosimetry models that are more important for alpha-emitting radionuclides than for fission and activation products. The aim is to develop estimates of uncertainty in dose coefficients for fission and activation products or plutonium that do not underestimate the uncertainty for any organ or tissue. We estimate these uncertainties on the basis of published assessments of uncertainties in dose coefficients discussed in the following section and the use of judgment in evaluating and applying the results of those assessments.

**4.1.5.3** *Assessments of Uncertainty in Dose Coefficients*. Several published assessments of uncertainty in dose coefficients for inhalation or ingestion of radionuclides were considered in developing probability distributions of dose coefficients for inhalation of fission and activation products or plutonium in respirable or nonrespirable form used in this analysis.

**4.1.5.3.1** *Assessment by NCRP*. An assessment of the reliability of effective dose coefficients for several radionuclides in healthy adult males, as calculated using dosimetric and biokinetic models that were recommended in ICRP Publication 30 (ICRP, 1979), was performed

by NCRP (1998); see also Bouville et al. (1994).[49] Results of NCRP's assessment are summarized in Table 4-8. Estimated uncertainties range from a factor of 2 or 3 (e.g., for intakes of $^{90}$Sr, $^{131}$I, and $^{137}$Cs) to a factor of 10 (e.g., for ingestion of $^{144}$Ce and intakes of $^{239}$Pu).

We note the following points about NCRP's estimates of reliability in dose coefficients. First, uncertainties in dose coefficients for specific organs or tissues, especially minor sites of deposition, could be substantially larger than uncertainties in effective dose coefficients. Second, NCRP's assessment focused on dose coefficients for soluble forms of radionuclides, and estimates of reliability may not apply to less soluble forms of some radionuclides that are expected to occur in fallout. Finally, NCRP's estimates of reliability represent subjective judgment, rather than results of an analysis of uncertainty in dosimetric and biokinetic models due to uncertainties in model parameters, and they were based mainly on judgments about the quality of available data on biokinetic behavior.[50] Therefore, it is questionable whether NCRP's assessment adequately represents uncertainties in dose coefficients for specific organs or tissues from inhalation or ingestion of radionuclides in fallout.

**4.1.5.3.2** *Assessment in EPA's federal guidance*. EPA's Federal Guidance Report No. 13 (Eckerman et al., 1999) includes an assessment of uncertainties in risk coefficients for inhalation or ingestion of radionuclides in the environment; this assessment has been updated by Pawel et al. (2007). EPA's risk coefficients give estimates of lifetime cancer mortality or morbidity (incidence) per unit activity intake of radionuclides in a population of all ages—i.e., these are age- and gender-averaged risks. EPA's assessment of uncertainties in risk coefficients considered uncertainties in (1) estimates of the risk per unit absorbed dose in specific organs or

[49] Although the quantity for which reliability was estimated was referred to as an "effective dose coefficient," dose coefficients evaluated by NCRP were effective dose equivalents as defined in ICRP Publication 26 (ICRP, 1977), rather than effective doses as defined in ICRP Publication 60 (ICRP, 1991). This difference is not important for purposes of our analysis.

[50] The importance of NCRP's focus on data quality is indicated by the following example (R.W. Leggett, Oak Ridge National Laboratory, personal communication). The dose coefficient for inhalation of $^{95}$Zr was assigned a low reliability by NCRP. However, a sensitivity analysis would show that estimates of effective dose equivalent in that case are rather insensitive to gaps in biokinetic data, because the effective dose equivalent is dominated by the dose to the lung, an organ in which the dosimetry and biokinetic behavior of radionuclides is relatively well characterized. Therefore, the uncertainty in the effective dose coefficient for inhalation of $^{95}$Zr probably is substantially less than the estimated reliability in Table 4-8. A similar conclusion may apply in other cases.

tissues, including uncertainties in a tissue-specific dose and dose-rate effectiveness factor (DDREF) for photons and electrons[51] and the relative biological effectiveness (RBE) of alpha particles, and (2) estimates of absorbed dose to specific organs or tissues due to uncertainties in dosimetric and biokinetic models currently recommended by ICRP [(1996a; 2002) and references therein]. Uncertainties in risk models were judged to be important in all cases.

Selected results of EPA's assessment of uncertainties in risk coefficients are summarized in Tables 4-9 and 4-10. Uncertainties were divided into five categories that are defined by ratios of upper bounds (upper 95% credibility limits) of risk coefficients to lower bounds (lower 5% credibility limits). Uncertainty factors in Table 4-10 can be compared, for example, with the corresponding uncertainty factors from NCRP's assessment in Table 4-8. Given the importance of uncertainty in the risk model in all cases, EPA's estimates of uncertainty in dose coefficients would be less than the estimates of uncertainty in risk coefficients.

The following points about EPA's estimates of uncertainty in risk coefficients should be noted. First, risk coefficients are determined primarily by doses and risks at major sites of deposition in the body, and uncertainties at minor sites of deposition, especially uncertainties in doses per unit activity intake of radionuclides, could be larger. Second, to the extent that risk coefficients are dominated by the risks due to intakes by younger age groups in a population of all ages, uncertainties in risk coefficients that would apply to intakes by adults could be overestimated in many cases, because risks per unit absorbed dose and the biokinetic behavior of radionuclides often are better understood in adults than in younger age groups. Third, EPA's judgments about uncertainties in risks per unit absorbed dose in specific organs or tissues were based on results of an expert elicitation (Little et al., 1997), rather than an analysis of available data, such as an analysis performed by EPA (1994; 1999). EPA thus assumed that an inconsistency in estimates of risk by different experts is a valid measure of uncertainty. This approach may inflate the importance of uncertainties in risks per unit absorbed dose in some organs or tissues relative to uncertainties in doses per unit activity intake of radionuclides (Pawel et al., 2007). Finally, EPA's analysis applies to chemical forms of radionuclides that are

[51] A DDREF takes into account that the risk per unit absorbed dose of low-LET radiations may be lower at low doses or low dose rates than at higher acute doses in Japanese atomic-bomb survivors. In radiation protection, for example, a DDREF of 2 usually is assumed (ICRP, 1991; NCRP, 1993).

expected to be the most important in releases from nuclear facilities or natural sources, and assumed biokinetic models may not always apply to chemical forms in fallout. The last point could be especially important in considering uncertainties in EPA's risk coefficients for ingestion, because ingested radionuclides were assumed to occur in tap water or foods and chemical forms in those sources often should be more soluble than chemical forms in fallout.

**4.1.5.3.3** *Assessment in NRC-CEC expert elicitation*. In a study conducted for the U.S. Nuclear Regulatory Commission (NRC) and Commission of the European Communities (CEC), a group of experts was asked to estimate median values and 90% credibility intervals of committed dose coefficients for selected radionuclides and organs or tissues (Goossens et al., 1998); see also Harrison et al. (1998). A summary of results of the expert elicitation is given in Table 4-11. Estimated dose coefficients are absorbed doses per unit activity intake.

In all cases, results in Table 4-11 indicate that the difference between the experts' aggregated median estimate of a dose coefficient and the point value currently recommended by ICRP is negligible compared with the experts' aggregated estimate of uncertainty. In many cases, the experts' estimated uncertainty (ratio of the 95$^{th}$ to the 5$^{th}$ percentile) is much larger than the uncertainty in the corresponding effective dose coefficient in Table 4-8 or risk coefficient in Table 4-10.[52] Large uncertainties in Table 4-11 may be due, at least in part, to differences in assumptions by each expert about absorption of radionuclides in the lungs and GI tract, and its uncertainty, that could arise from uncertainty in their chemical form. Effects of changes in chemical form were not considered in analyses summarized in Tables 4-8 and 4-10.

Uncertainties in Table 4-11 take into account differences in median dose coefficients that were estimated by each expert as well as each expert's ratio of the 95$^{th}$ to the 5$^{th}$ percentile. Thus, an uncertainty can be greatly influenced by the median and 90% credibility interval that was estimated by a single expert when that expert's estimates differ greatly from all the others. To investigate this effect, we examined estimates by each expert in all cases where the uncertainty in Table 4-11 is a factor of 400 or greater. Medians and 90% credibility intervals of dose coefficients that were estimated by each expert in those cases are given in Table 4-12. If

[52] Ratios of the 95$^{th}$ to the 5$^{th}$ percentile of probability distributions can be compared with ratios of the 95$^{th}$ to the 50$^{th}$ percentile by taking the square root of the former or by squaring the latter.

the case of the dose to bone surfaces from inhalation of $^{144}Ce$ is excluded on the grounds that the uncertainties in Tables 4-11 and 4-12 are inconsistent, a single set of estimates by one expert that differed greatly from all the other experts' estimates is seen in most cases. The existence of an outlier is especially evident when the uncertainty in Table 4-11 exceeds a factor of 1,000.

We believe that there are important flaws in the NRC-CEC expert elicitation that cast doubt on the value of the results in providing reasonable estimates of uncertainty in dose coefficients. For example, the method used to aggregate the results provided by each expert to obtain the uncertainties in Table 4-11 (Goossens et al., 1998, Vol. 1) incorporates a questionable assumption that probably resulted in artificially high estimates of uncertainty. Specifically, each expert's $95^{th}$ and $5^{th}$ percentiles of a dose coefficient were assumed to define upper and lower bounds of a uniform or log-uniform probability distribution; a uniform distribution was assumed when the uncertainty was relatively small, and a log-uniform distribution was assumed when the uncertainty was relatively large. An important consequence of those assumptions is that intermediate values in a probability distribution were not given greater weight than one or both of the bounding values. This is a particularly important concern when a log-uniform distribution is assumed, because the largest probability is assigned to the lowest value in an assumed range and the probability decreases monotonically with increasing value across the range. By weighting bounding values of each expert's distribution in those ways, which we believe is unreasonable, a larger uncertainty in aggregated results is obtained than would be obtained by assuming probability distributions in which intermediate values are given greater weight than values near the extremes (e.g., lognormal distributions).

We also have concerns about the design and execution of the expert elicitation. An examination of the responses provided by each participant (Goossens et al., 1998, Vol. 2) indicated to us that the number of questions posed in the elicitation was overwhelming to some participants, that many participants were not experts on some topics they were asked to address, and that the level of effort and study in responding to the elicitation varied considerably among the participants. Thus, the large uncertainties that were generated in many cases by combining median values and uncertainties that were provided by each participant probably are not a

reasonable representation of uncertainties in current information about the dosimetry and biokinetics of inhaled or ingested radionuclides.

**4.1.5.3.4** *Assessments by ICRP*. An ICRP task group has undertaken several assessments of uncertainties in dose coefficients for inhalation or ingestion of radionuclides by members of the public (Leggett, 2001, 2003; Harrison et al., 2001); see also Leggett et al. (1998).

Of particular interest to our analysis is an assessment of uncertainty in the GI-tract absorption fraction ($f_1$) for various radionuclides in adults and the effect of that uncertainty on uncertainty in the committed effective dose from ingestion (Harrison et al., 2001). Results of that assessment are summarized in Table 4-13. The uncertainty in $f_1$, which is expressed as the ratio of the 95$^{th}$ to the 5$^{th}$ percentile of a subjective probability distribution, is as high as a factor of 10 for $^{60}$Co and $^{239}$Pu, 20 for $^{106}$Ru, and 100 for $^{95}$Zr and $^{125}$Sb. However, data in animals suggest that the uncertainty in $f_1$ for plutonium in oxide form could be much greater than a factor of 10 (Harrison et al., 2001). Only for longer-lived radionuclides is the uncertainty in the committed effective dose from ingestion due to the uncertainty in $f_1$ usually about the same as the uncertainty in $f_1$ itself. For most shorter-lived radionuclides (i.e., $^{60}$Co, $^{95}$Zr, $^{106}$Ru, and $^{125}$Sb), a large uncertainty in $f_1$ has only a small effect on uncertainty in the committed effective dose, because the effective dose is dominated by calculated doses to walls of the stomach and colon during passage through the GI tract and the effective dose thus is insensitive to variations in $f_1$. However, for all radionuclides, an uncertainty in $f_1$ usually would lead to a comparable uncertainty in doses to specific organs or tissues following absorption in the GI tract.

**4.1.5.3.5** *Other assessments*. Several other assessments of uncertainty in dose coefficients for inhalation or ingestion of radionuclides are discussed below.

Assessment of doses from off-site fallout at NTS. In an assessment of doses to the public from exposure to fallout from weapons tests at NTS, Ng et al. (1990) estimated uncertainties in inhalation and ingestion dose coefficients for a large number of radionuclides. For inhalation of radionuclides that were assumed to be attached to particles with an AMAD of 1 μm, an uncertainty represented by a GSD of 1.8 was assigned to most combinations of radionuclide, organ, and age group, although a GSD as high as 2.0 was assigned in some cases; in a lognormal distribution, a GSD of 1.8 corresponds to a ratio of the 95$^{th}$ to the 50$^{th}$ percentile of 2.6. For

ingestion, a GSD of 1.3−1.8 was estimated for isotopes of strontium, iodine, and cesium, and a default GSD of 1.8 was assigned to all other radionuclides. However, estimated uncertainties in dose coefficients for isotopes of strontium apparently did not take into account an uncertainty in the dosimetric model for beta particles emitted by strontium and any decay products in the skeleton (Eckerman et al., 1999), and the assigned uncertainty in dose coefficients for most radionuclides, for which radionuclide-specific data were lacking, is a default value that was based on assumed uncertainties in dose coefficients for isotopes of strontium, iodine, and cesium. Therefore, we believe that many uncertainties in dose coefficients estimated by Ng et al. (1990) are too small.

Assessment of uncertainty in ICRP's respiratory-tract model. Bolch et al. (2001; 2003) and Farfán et al. (2003) performed a detailed analysis of uncertainties in ICRP's current model of the respiratory tract (ICRP, 1994) in cases of inhalation of insoluble plutonium and uranium oxides that are attached to monodisperse, unit-density spheres of diameter 0.001–50 μm; see also Huston (1995). At all diameters, the median dose to the lung, which was calculated as a weighted sum of the doses to different tissues,[53] differed from a point estimate that was calculated using ICRP's recommended parameter values by less than a factor of 2. Uncertainties in lung doses, which were expressed as ratios of the 95$^{th}$ to the 5$^{th}$ percentile of probability distributions, ranged from nearly a factor of 10 at particle diameters less 2 μm to as high as a factor of about 700 at diameters greater than 10 μm; the corresponding uncertainty factors (ratios of the 95$^{th}$ to the 50$^{th}$ percentile) range from about 3 to more than 25.

The largest uncertainties apply to nonrespirable particles for which the dose to the lung is very low compared with the dose from inhalation of respirable particles. For $^{239}PuO_2$ attached to monodisperse particles of diameter less than 10 μm, uncertainties in doses to the bronchial (BB) and bronchiolar (bb) regions and the thoracic lymph nodes ($LN_{th}$) were considerably larger than the uncertainty in the dose to the lung, ranging from a factor of about 20 to about 700; the corresponding uncertainty factors ranged from more than 4 to more than 25. At particle sizes

[53] Doses to the lung were calculated from doses to the bronchial (BB), bronchiolar (bb), and alveolar-interstitial (AI) regions and the dose to lymphatic tissues (LN) that drain those regions by assigning a weight of 0.001 to the dose to lymphatic tissues and a weight of 0.333 to each of the doses to the other three regions (ICRP, 1994).

between 1 and 10 μm, however, the uncertainty in the dose to all tissues except basal cells of the BB region decreased as the GSD of the distribution of particle sizes increased from 1 (monodisperse particles) to 4 (Huston, 1995). At a particle size of 10 μm, for example, the uncertainty factor for the dose to the lung decreased from about 10 for monodisperse particles to less than 2 for a distribution of particle sizes with a GSD of 2.0. Doses to the BB region were nearly independent of the assumed GSD of the distribution of particle sizes.

The analyses summarized above indicate that uncertainties in doses to the lung from inhalation of insoluble plutonium oxide in a distribution of particle sizes are not large.

Assessments of uncertainty for selected fission and activation products. Apostoaei et al. (1999) estimated uncertainties in organ-specific dose coefficients for ingestion of $^{60}$Co and $^{106}$Ru. GSDs of 3.2 for $^{60}$Co and 3.0 for $^{106}$Ru were obtained. Those estimates correspond to uncertainty factors (ratios of the 95$^{th}$ to the 50$^{th}$ percentile) of about 7 and 6, respectively. Uncertainties in organ-specific dose coefficients for ingestion of $^{131}$I, $^{137}$Cs, and $^{90}$Sr also were estimated, as discussed below.

Apostoaei and Miller (2004) performed a detailed analysis of uncertainties in dose coefficients for ingestion of $^{131}$I, $^{137}$Cs, and $^{90}$Sr. For $^{90}$Sr, estimated uncertainties are represented by a GSD of 2.6 for bone surfaces, 2.4 for red bone marrow, and 1.8 or less for most other organs. For $^{131}$I, the uncertainty in the dose coefficient for the thyroid is represented by a GSD of 1.7, and the uncertainty in the dose coefficient for $^{137}$Cs and any organ in males is represented by a GSD of 1.24. The estimated uncertainties for $^{131}$I and $^{137}$Cs thus are similar to other estimates in Tables 4-8 and 4-11 and earlier estimates by Dunning and Schwarz (1981) and Matthies et al. (1981).[54] However, comparisons with estimated uncertainties in risk coefficients in Table 4-10 are difficult when the importance of uncertainties in cancer risks per unit absorbed dose to those results is unknown to us. The estimated uncertainties for $^{90}$Sr are somewhat larger than the estimate in Table 4-8 when the dominant importance of doses to bone surfaces and red bone marrow in determining the effective dose is taken into account; the ratio of the 95$^{th}$ to the 50$^{th}$ percentile of the probability distribution of the effective dose coefficient obtained from the

[54] The comparison with estimated uncertainties in Table 4-8 takes into account that the effective dose from $^{131}$I is determined by the equivalent dose to the thyroid, and that the effective dose from $^{137}$Cs is about the same as the equivalent dose to any organ or tissue (ICRP, 2002).

results of Apostoaei and Miller (2004) is about 5. However, estimated uncertainties for $^{90}Sr$ are much smaller than those in Table 4-11—i.e., ratios of the 95$^{th}$ to the 5$^{th}$ percentile of the probability distributions of dose coefficients for the colon, red bone marrow, and bone surfaces are about 7, 18, and 23, respectively, compared with ratios of 600, 240, and 390 in Table 4-11. The much larger uncertainties that were obtained in the NRC-CEC expert elicitation were due primarily to differences in the median estimates of dose coefficients by different experts, because ratios of the 95$^{th}$ to the 5$^{th}$ percentile estimated by each expert (Goossens et al., 1998, Vol. 2; Appendix C) were much less than uncertainties in Table 4-11 that represent the combined estimates of all experts. As discussed in Section 4.1.5.3.3, differences in the median estimates of dose coefficients by different experts may be due, at least in part, to different assumptions about absorption in the GI tract, and it is doubtful that the expert elicitation provides reasonable estimates of uncertainty in many cases.

Assessment of uncertainties in dose coefficients for plutonium. In an assessment of cancer risks from inhalation of plutonium and their uncertainties, Grogan et al. (2000; 2001) estimated uncertainties in organ-specific absorbed dose coefficients for inhalation of insoluble plutonium oxide. Organs and tissues that were considered in that analysis include the lung, liver, bone, and red bone marrow. The AMAD of inhaled particles was assumed to be 1, 5, or 10 μm, and the GSD of all particle-size distributions was assumed to be 2.5. Estimated uncertainties in absorbed dose coefficients, as represented by GSDs, for inhalation of plutonium oxide at the three particle sizes are summarized as follows:

- AMAD of 1 μm – GSD of 1.9 for the lung and 3.0 for the liver, bone, and red bone marrow; the corresponding uncertainty factors (ratios of the 95$^{th}$ to the 50$^{th}$ percentile) are 2.9 and 6.1, respectively;
- AMAD of 5 μm – GSD of 2.7 for the lung and 3.5 for the liver, bone, and red bone marrow; the corresponding uncertainty factors are 5.1 and 7.9, respectively;
- AMAD of 10 μm – GSD of 4.3 for the lung and 4.5 for the liver, bone, and red bone marrow; the corresponding uncertainty factors are 11 and 12, respectively.

**4.1.5.4** *Present Assessment of Uncertainties in Dose Coefficients*. In this analysis, uncertainties in dose coefficients for inhalation of fission and activation products in respirable or nonrespirable form are assessed separately from uncertainties in dose coefficients for plutonium. This separation is appropriate when uncertainties in dosimetric models can be more important for alpha-emitting radionuclides than for beta/gamma emitters (Eckerman et al., 1999; Pawel et al., 2007). As discussed in Section 4.1.5.2, an approach that is both practical and consistent with current methods of dose reconstruction for military participants is to develop two estimates of uncertainty that apply to all organs or tissues, one estimate for inhalation of any mixture of fission and activation products in respirable or nonrespirable form and the other for inhalation of plutonium in either form.

Uncertainties in dose coefficients for inhalation of radionuclides in respirable or nonrespirable form are estimated in the following way. We first estimate uncertainties in dose coefficients that are calculated using dosimetric and biokinetic models currently recommended by ICRP. We then consider an uncertain bias factor, which is intended to take into account that dose coefficients calculated by ICRP may overestimate values that apply to chemical and physical forms of radionuclides in fallout, especially in cases of inhalation of large, nonrespirable particles (see Section 4.1.5.2). When such a bias factor is assumed to apply, an uncertainty in dose coefficients is estimated by combining an assumed uncertainty in ICRP's dose coefficients with an uncertain bias factor.

Our assessment of uncertainties in dose coefficients incorporates two assumptions implicitly. First, in accordance with policy and procedures of the NTPR Program (DTRA, 2007; Case et al., 2008), we assume that internal doses to military participants will be estimated using dose coefficients for adult members of the public currently recommended by ICRP [(1996a; 2002) and references therein], rather than dose coefficients based largely on earlier recommendations (ICRP, 1979), which were used in dose reconstructions until recently, and we further assume that dose coefficients for radionuclides in oxide form will be used, as has generally been the case in dose reconstructions (Egbert et al., 1985; Raine et al., 2007).

Second, if ingestion dose coefficients are used to estimate doses from inhalation of large, nonrespirable particles, we assume that values currently recommended by ICRP would be

reduced by a factor of about 4 to account for assumptions in the current respiratory-tract model that about half of all large particles that are inhaled are deposited in the nose, throat, and mouth, and that about half of the deposited material is transferred to the GI tract by swallowing (ICRP, 1994). As noted in Section 3.1, dose reconstructions that were performed until recently assumed that nearly all large inhaled particles are transferred to the GI tract (ICRP, 1979).

**4.1.5.4.1** *Uncertainty in ICRP's dose coefficients for fission and activation products*. Many fission and activation products are potentially important in inhalation exposures of military participants, and the important radionuclides and their relative activities vary with time after a detonation (Egbert et al., 1985; Raine et al., 2007). However, as indicated by studies discussed in Section 4.1.5.3, uncertainties in dose coefficients for inhalation or ingestion of fission and activation products appear to be reasonably well characterized for only a few combinations of radionuclide and organ or tissue, including $^{131}$I (thyroid), $^{90}$Sr (bone surfaces, red bone marrow, and various soft tissues), and $^{137}$Cs (all organs and tissues).

Development of a probability distribution to represent uncertainties in dose coefficients for inhalation of fission and activation products in respirable or nonrespirable form for purposes of this analysis is not straightforward, given that (1) uncertainties are radionuclide-specific and, for a given radionuclide, organ-specific, and (2) radionuclides that contribute significantly to dose depend on the organ or tissue of concern and the time after a detonation when exposure to fallout from that detonation occurred. For example, if exposure occurred a few years after a detonation and inhalation of nonrespirable particles is assumed, important fission products include $^{90}$Sr, which mainly irradiates bone surfaces and red bone marrow, $^{106}$Ru and $^{144}$Ce, which mainly irradiate the lower GI tract, and $^{137}$Cs, which irradiates all organs and tissues nearly uniformly. In addition, uncertainties in dose coefficients for inhalation or ingestion have not been studied for some potentially important fission and activation products, and uncertainties in dose coefficients at minor sites of deposition in the body could be large even for well-studied radionuclides, due to uncertainties in deposition fractions at those sites.

Our estimate of uncertainty in ICRP's dose coefficients for inhalation of fission and activation products in respirable or nonrespirable form is based on assessments of uncertainties in dose coefficients discussed in Section 4.1.5.3, except little credence is given to the large

uncertainties that were obtained in the NRC-CEC expert elicitation (see Section 4.1.5.3.3 and Table 4-11). Additional considerations are needed when exposure to mixtures of fission and activation products occurs, as was the case in exposures of military participants. For example, unless there are strong correlations among dose coefficients for important radionuclides (i.e., all dose coefficients that apply to an individual's organ or tissue of concern would be larger or smaller than values calculated by ICRP, rather than randomly distributed about ICRP's calculated values), the uncertainty in a dose coefficient for mixtures of radionuclides (i.e., ratio of the $95^{th}$ to the $50^{th}$ percentile) should be no larger than the largest uncertainty that applies to any radionuclide in a mixture when exposures generally should involve some radionuclides for which the uncertainty is relatively small. On the other hand, some correlation among dose coefficients for different radionuclides is expected and, therefore, adding doses from different radionuclides should not always reduce the overall uncertainty by a large amount. For example: (1) dose coefficients for isotopes of strontium and barium, which are bone-seeking alkaline-earth elements (Group IIA), probably are correlated to a significant extent, but dose coefficients for isotopes of cesium (alkaline metal, Group IA) and cerium (lanthanide series) should have little correlation; (2) dose coefficients for source organs should be negatively correlated with organ mass (i.e., a lower organ mass results in a higher dose from all deposited radionuclides, and vice versa, if deposition fractions do not depend on organ mass); and (3) some correlation in GI tract absorption of different radionuclides is expected when there should be a tendency for all insoluble oxide forms of radionuclides to be more strongly or more weakly absorbed in an individual than is assumed by ICRP and ingestion of large, insoluble fallout particles could result in very low absorption of all refractory radionuclides that are dispersed in the volume of such particles, compared with ICRP's assumptions.

By considering available information on uncertainties in dose coefficients for inhalation and ingestion and the complicating factors that arise in applying that information to mixtures of radionuclides, it is our judgment that a reasonable estimate of uncertainty in dose coefficients for inhalation of mixtures of fission and activation products in respirable or nonrespirable form currently recommended by ICRP is a factor of 10. We represent this uncertainty by a lognormal probability distribution with a 90% credibility interval between 0.1 and 10.

The choice of an uncertainty factor of 10 is supported by the following rationale. Although uncertainties in dose coefficients for certain radionuclides at minor sites of deposition in the body could be more than a factor of 10, such large uncertainties should be compensated to a significant extent by (1) the presence of several fission and activation products in all exposures to resuspended fallout at NTS, (2) the lower uncertainties in dose coefficients at minor sites of deposition for at least some important radionuclides, and (3) a lack of correlation in dose coefficients for at least some important radionuclides. When exposure to fallout that was deposited a few years previously occurred, fewer fission and activation products would be of concern, and these compensating factors could be less significant. However, we do not expect that exposures in the thermal-pulse and blast-wave regions at NTS only involved fallout that was deposited a few years previously, without the presence of significant quantities of more recent fallout that contained many fission and activation products.

The uncertainty in dose coefficients for mixtures of fission and activation products could be substantially less than a factor of 10, especially when exposure to a large number of those radionuclides occurred. A smaller uncertainty might apply, for example, when uncertainties in dose coefficients for important radionuclides are less than a factor of 10 or are uncorrelated. However, we believe that it is difficult to justify a lower uncertainty factor that would apply to all possible mixtures of fission and activation products and all organs or tissues of concern. In addition, it is important that this uncertainty not be underestimated when effective resuspension factors derived in this report are to be used in dose reconstructions for military participants and estimated doses should be at least upper 95% credibility limits of possible doses.

**4.1.5.4.2** *Uncertainty in ICRP's dose coefficients for plutonium*. As noted in Section 4.1.2.4, measurements at NTS after the period of weapons testing indicated that plutonium was the most important alpha-emitting radionuclide in fallout, and that other alpha emitters, such as $^{241}$Am and $^{238}$Pu, were relatively unimportant (McArthur, 1991).[55] An

[55] If other alpha-emitting radionuclides were important, dose coefficients for all such radionuclides are expected to be highly correlated, due mainly to their similar biokinetic behavior [ICRP (1996a; 2002) and references therein]. Therefore, in contrast to the case of mixtures of fission and activation products, it would not be appropriate to consider that dose coefficients for different alpha emitters are uncorrelated in assessing uncertainties in dose coefficients for mixtures of such radionuclides.

evaluation of uncertainties in organ-specific dose coefficients for inhalation of plutonium in respirable or nonrespirable form requires a consideration of uncertainties in dosimetric and biokinetic models.

An uncertainty in the biological effectiveness of alpha particles relative to photons and electrons also contributes to uncertainties in equivalent doses to specific organs or tissues per unit activity intake of plutonium. However, given that probability distributions of radiation effectiveness factors (REFs) that were developed by Kocher et al. (2002; 2005) to represent the biological effectiveness of alpha particles in inducing cancer in humans are incorporated in the computer code that is used to evaluate causation of cancers in military participants when a dose reconstruction is required (Land et al., 2003; Kocher et al., 2008), an uncertainty in the biological effectiveness of alpha particles is not taken into account in this analysis. Taking uncertainties in REFs into account would result in a double counting of this source of uncertainty.

We assume that uncertainties in dose coefficients for inhalation or ingestion of plutonium due to uncertainties in dosimetric and biokinetic models should be substantially larger than uncertainties in dose coefficients for mixtures of beta/gamma-emitting fission and activation products. This assumption is based mainly on two considerations: (1) the greater importance of uncertainties in dosimetric models for alpha-emitting radionuclides in some organs or tissues (e.g., the skeleton and GI tract) compared with uncertainties in dosimetric models for beta/gamma emitters and (2) the larger uncertainty in absorption of plutonium in the GI tract compared with uncertainties in GI-tract absorption for many fission and activation products (Eckerman et al., 1999; Harrison et al., 2001; Pawel et al., 2007). Estimated uncertainties in dose or risk coefficients for plutonium that were obtained in studies summarized in Tables 4-8 and 4-10 are among the highest for any radionuclide.

For purposes of this analysis, it is our judgment that a reasonable estimate of uncertainty in dose coefficients for inhalation of plutonium in respirable or nonrespirable form currently recommended by ICRP is a factor of 30. We represent this uncertainty by a lognormal probability distribution with a 90% credibility interval between 0.033 and 30.

The choice of an uncertainty factor of 30 is based mainly on three considerations. First, data in animals discussed by Harrison et al. (2001) and noted in Table 4-13 suggest that the

uncertainty in the GI-tract absorption fraction for plutonium in oxide form (i.e., the ratio of the 95$^{th}$ to the 50$^{th}$ percentile) could be a factor of about 10. Data in Table 4-13 indicate that an uncertainty factor of 10 also applies to a few other radionuclides for which the GI-tract absorption fraction is poorly known. Second, given that data in humans on accumulation of plutonium at minor sites of deposition (i.e., sites other than the lung, skeleton, liver, and gonads) are not extensive and show considerable variability (ICRP, 1993), we believe that the uncertainty in the deposition fraction at minor sites could be as high as a factor of 10. By combining these two uncertainties, which should be uncorrelated, an uncertainty factor of about 27 is obtained. Third, we assume that uncertainties in dosimetric modeling of plutonium contribute to the overall uncertainty, even in estimating dose in soft tissues. An uncertainty in dosimetric modeling in soft tissues occurs, for example, when the particular location of deposited plutonium with respect to radiosensitive cells in which cancer would be induced is uncertain. This uncertainty can be important due to the very short ranges of alpha particles in tissue.

An estimated uncertainty of about a factor of 8–12 in the risk coefficient for ingestion of plutonium in EPA's Federal guidance (see Tables 4-9 and 4-10) is much lower than the uncertainty factor of 30 used in this analysis. Similarly, the analyses by Bolch et al. (2001; 2003), Farfán et al. (2003), and Grogan et al. (2000; 2001) discussed in Section 4.1.5.3.5 indicate that uncertainties in dose coefficients for inhalation of plutonium in respirable form could be less in some organs or tissues than uncertainties in dose coefficients for ingestion (i.e., inhalation of plutonium in nonrespirable form). However, such differences are not taken into account in this analysis when other assessments focused on dose coefficients at major sites of deposition but we are concerned with dose coefficients at minor sites as well. We also note that assessments of uncertainty in dose coefficients for ingestion of plutonium focused on more soluble chemical forms, rather than insoluble oxide forms of interest in exposures to fallout. However, we believe that the dependence of uncertainties in dose coefficients on chemical form should be substantially less than the dependence of dose coefficients themselves. That is, uncertainties in dose coefficients for plutonium oxide should be similar to uncertainties in dose coefficients for other chemical forms, even though dose coefficients for the two forms may differ substantially.

**4.1.5.4.3** *Bias in ICRP's dose coefficients*. Uncertainties in dose coefficients for inhalation of radionuclides in respirable or nonrespirable form that were developed in the previous two sections are intended to apply to dose coefficients for adult members of the public and for radionuclides in oxide form currently recommended by ICRP [(1996a; 2002) and references therein]. However, as noted in Section 4.1.5.2, ICRP's dose coefficients may tend to overestimate values that apply to radionuclides in fallout at NTS, due primarily to the preponderance of large particles in fallout at locations close to ground zero and their low solubility. The possibility that use of ICRP's dose coefficients results in substantial overestimates of internal doses to military participants was noted in a previous review of methods of dose reconstruction (NRC, 1985).

We assume that a possible bias in ICRP's dose coefficients is important for inhalation of larger, nonrespirable particles (i.e., ingestion) but is not important for inhalation of smaller, respirable particles. The latter assumption is based on data which indicate that the solubility of smaller fallout particles is substantially higher than the solubility of larger particles (Larson et al., 1966; LeRoy et al., 1966) and the consideration that absorption of beta and alpha radiation in fallout particles of diameter less than 10 μm should not be important. Biases in ICRP's dose coefficients for ingestion are considered below.

Bias in dose coefficients for ingestion of fission and activation products. We are aware of two sources of data on a possible bias in ICRP's dose coefficients for ingestion of fission and activation products in fallout. Glasstone and Dolan (1977; Paragraph 12.169) noted, without attribution, that about 10% of ingested strontium and barium oxide in early fallout is absorbed into blood. Compared with ICRP's current assumptions that 30% of strontium oxide and 10% of barium oxide is absorbed in the GI tract (ICRP, 1996a; 2002), the estimate of 10% noted by Glasstone and Dolan suggests that ICRP's dose coefficients for radioisotopes of those elements could be too high by a factor of about 2 when they are applied to nonrespirable fallout particles.[56] A bias of a factor of 2 should be a minimum value for mixtures of fission and activation products when it is considered that (1) strontium and barium oxide are considerably

[56] This conclusion takes into account that the total activities of shorter-lived isotopes of strontium and barium in fresh fallout are about the same (Trabalka and Kocher, 2007).

more soluble than oxide forms of many other elements (ICRP, 1996a; 2002) and (2) strontium and barium tend to be volatile elements that are preferentially deposited on the surface of fallout particles (Freiling et al., 1965; Hicks, 1982) and, thus, should be more available to be dissolved than refractory elements (e.g., cerium).

The second source of data is a study on human subjects who ingested fallout particles of different sizes that were collected at 5 days after a detonation at NTS (LeRoy et al., 1966). At particle sizes less than about 180 μm, which are of greatest interest in evaluating a possible bias in ICRP's dose coefficients for inhalation of nonrespirable particles, the fraction of the total activity of photon-emitting radionuclides that was absorbed in the GI tract ranged from about 0.01 to 0.09, and the average absorption fraction was about 0.05.[57] In comparison, on the basis of estimates of the relative activities of fission and activation products in fallout at 2 days after a detonation (Trabalka and Kocher, 2007), we estimate that the average absorption fraction would have been between 0.1 and 0.2 if GI-tract absorption fractions for oxide forms recommended by ICRP (1996a; 2002) applied to ingestion of radionuclides in fallout particles, depending on assumptions about the extent to which isotopes of iodine were retained on fallout particles prior to ingestion by study subjects. This comparison indicates that ICRP's dose coefficients for ingestion could be too high by a factor of about 2−4 when they are applied to mixtures of many fission and activation products in nonrespirable fallout particles.

On the basis of the limited data and analysis described above, we assume that the bias in ICRP's dose coefficients for ingestion of fission and activation products when they are applied to inhalation of fallout particles in nonrespirable form should not exceed a factor of 4. Since the data also indicate that the bias could be very small if particles were sufficiently small to be inhalable, we represent the uncertainty in the bias in ICRP's dose coefficients for ingestion by a uniform distribution between 0.25 and 1.0. Thus, we assume that, on average, ICRP's dose coefficients for ingestion of fission and activation products overestimate values that apply to inhalation of nonrespirable fallout particles by less than a factor of 2.

[57] In developing these estimates, we ignored results for two subjects in which the activity absorbed in the GI tract was too low to be detected above a background count rate (LeRoy et al., 1966).

Bias in ingestion dose coefficients for plutonium. We are unaware of any published studies on absorption of plutonium in the GI tract following ingestion of fallout particles. However, we believe it is reasonable to assume that the bias in ICRP's dose coefficients for ingestion of plutonium in oxide form when they are applied to inhalation of nonrespirable fallout particles should be larger than the assumed bias in ICRP's dose coefficients for inhalation of fission and activation products in nonrespirable form given above. Our reasoning is that plutonium, which is highly refractory (Freiling et al., 1965; Hicks, 1982), should be distributed in the volume of insoluble fallout particles to a greater extent than mixtures of fission and activation products, which include refractory and volatile radionuclides.

In the absence of data, an assumption about the bias in ICRP's dose coefficients for ingestion of plutonium is based on judgment. In addition to assuming that the bias should be larger than the assumed bias for mixtures of fission and activation products, we assume that the uncertainty in the bias for plutonium should be larger. On the basis of these considerations, we assume that the bias in ICRP's ingestion dose coefficients for plutonium could range from 0.1 to 1.0, and we represent this assumption by a log-uniform probability distribution with a minimum at ($ln$ 0.1) = −2.3 and maximum at ($ln$ 1.0) = 0. The median of this distribution is 0.32, the mean is 0.39, and the 90% credibility interval ranges from 0.11 to 0.89. Thus, we assume that, on average, ICRP's dose coefficients for ingestion of plutonium oxide overestimate values that apply to inhalation of fallout particles in nonrespirable form by less than a factor of 3.

**4.1.5.5** *Summary of Uncertainties in Dose Coefficients*. Assumed uncertainties in the different factors that contribute to estimated uncertainties in dose coefficients for inhalation of fission and activation products or plutonium in respirable or nonrespirable form in resuspended fallout are summarized in Table 4-14. Representations of uncertainty in dose coefficients for inhalation of fission and activation products or plutonium in respirable or nonrespirable form used in this analysis are obtained by combining the probability distributions of the different parameters. The following medians and 90% credibility intervals of probability distributions to represent uncertainties in dose coefficients are obtained:

- Inhalation of fission and activation products in respirable form – Median at 1.0 and 90% credibility interval between 0.1 and 10;
- Inhalation of fission and activation products in nonrespirable form – Median at 0.6 and 90% credibility interval between 0.054 and 6.4;
- Inhalation of plutonium in respirable form – Median at 1.0 and 90% credibility interval between 0.033 and 30.
- Inhalation of plutonium in nonrespirable form – Median at 0.3 and 90% credibility interval between 0.0087 and 12.

These probability distributions represent the assumed uncertainties in dose coefficients that apply in the resuspension scenarios of concern at NTS relative to dose coefficients for adult members of the public currently recommended by ICRP. For example, for inhalation of plutonium in nonrespirable form, an upper 95% credibility limit of the dose coefficient to any organ or tissue is assumed to exceed ICRP's dose coefficient by a factor of 12.

For inhalation of radionuclides in nonrespirable form, assumed uncertainties in dosimetric and biokinetic models currently recommended by ICRP contribute 93% of the total uncertainty for fission and activation products and 91% of the total uncertainty for plutonium. Thus, this source of uncertainty is much more important that the assumed uncertainties in the bias in ICRP's dose coefficients when they are applied to inhalation of radionuclides in nonrespirable form.

The probability distributions of dose coefficients for inhalation of all radionuclides in respirable form summarized above are assumed to be lognormal. The probability distributions of dose coefficients for inhalation of radionuclides in nonrespirable form also are well represented by lognormal distributions with the indicated 90% credibility intervals. This is an expected result when the parameter with the largest uncertainty is assumed to be lognormally distributed. GSDs of lognormal probability distributions of dose coefficients with the indicated 90% credibility intervals for radionuclides in nonrespirable form are about 4.3 for fission and activation products and 9.0 for plutonium.

### 4.1.6 *Summary of Uncertainties in Estimates of Inhalation Dose*

Sections 4.1.1−4.1.5 present the assumed probability distributions of parameters in the model that is used in dose reconstructions to estimate doses from inhalation of resuspended radionuclides [see Section 3.1, eq. (5)] when that model is applied to resuspension of fallout in the thermal-pulse or blast-wave region of nuclear detonations at NTS. Except for the uncertainty in the breathing rate (see Section 4.1.4), assumed uncertainties in the different factors that contribute to uncertainties in estimated doses from inhalation of radionuclides in respirable or nonrespirable form are summarized in Tables 4-1, 4-7, and 4-14.

Assumed uncertainties in estimated concentrations of radionuclides in fallout that was deposited on the ground surface as those concentrations affect estimates of inhalation dose [i.e., the product of a measured photon exposure rate in air, $I$, and the radionuclide concentrations per unit exposure rate, $SA/I$, in eq. (5)], resuspension factors, the breathing rate, and dose coefficients for inhalation of radionuclides in respirable or nonrespirable form are summarized in Table 4-15 as median values and 90% credibility intervals. Since inhalation doses are estimated as the product of the parameters in Table 4-15, this summary permits a qualitative assessment of the relative importance of different sources of uncertainty. The assumed uncertainties in dose coefficients and resuspension factors clearly are the most important. The importance of the different parameters that contribute to those uncertainties is described in Sections 4.1.3.3 and 4.1.5.5.

## 4.2 Calculated Probability Distributions of Inhalation Dose

Assumed probability distributions of parameters in the model in eq. (5) (see Section 3.1), as summarized in Table 4-15, were combined (multiplied) using Latin Hypercube sampling as implemented by Crystal Ball® software (Decisioneering, 2001) (see Section 3.2) to generate probability distributions to represent estimated uncertainties in the equivalent dose to any organ or tissue from inhalation of radionuclides in respirable or nonrespirable form in fallout that was resuspended by nuclear detonations at NTS. In the following sections, results of these

calculations are presented separately for fission and activation products and for plutonium. In Section 5, these results are compared with point estimates of inhalation dose that would be obtained in dose reconstructions for military participants, as described in Section 3.1, to derive effective resuspension factors that should be assumed in the thermal-pulse and blast-wave regions to ensure that estimated doses are at least upper 95% credibility limits.

### **4.2.1** *Approach to Combining Parameter Uncertainties*

For each of the eight exposure situations of concern (inhalation of fission and activation products or plutonium in respirable or nonrespirable form in the thermal-pulse or blast-wave region), probability distributions to represent uncertainty in inhalation doses that are estimated using the model in eq. (5) can be obtained by combining (multiplying) the assumed probability distributions of each relevant parameter given in Tables 4-1, 4-7, and 4-14 and the assumed probability distribution of the breathing rate given in Section 4.1.4. However, a simpler approach is to assume that upper and lower bounds of the 90% credibility intervals of each parameter in Table 4-15 define $5^{th}$ and $95^{th}$ percentiles of lognormal probability distributions. Use of lognormal distributions to represent the calculated probability distributions of concentrations of radionuclides on the ground surface, resuspension factors, and dose coefficients is justified on the grounds that those distributions are well represented by lognormal distributions (see Sections 4.1.2.5, 4.1.3.3, and 4.1.5.5).

The adequacy of an assumption that upper and lower bounds of the 90% credibility intervals of the probability distributions of parameters in Table 4-15 other than the breathing rate, which is described by a lognormal distribution, define $5^{th}$ and $95^{th}$ percentiles of lognormal distributions was checked in two ways. The simplest way was to note that, for each parameter in Table 4-15, the geometric mean of the $5^{th}$ and $95^{th}$ percentiles, which is the median of a lognormal distribution, is close to the median of the probability distribution that was calculated using the assumed probability distributions of all relevant parameters. In the worst case, which occurs in the probability distribution of the concentrations of fission and activation products in nonrespirable form on the ground surface, the calculated median differs from the geometric mean

of the 5th and 95th percentiles by less than 10%. If the calculated probability distribution of a parameter in Table 4-15 deviated substantially from a lognormal distribution, the median would not be close to the geometric mean of the 5th and 95th percentiles. The adequacy of our assumption was also checked by fitting each continuous probability distribution that can be specified in Crystal Ball® to the calculated probability distributions and testing for goodness of fit (Decisioneering, 2001).[58] In all cases, a lognormal distribution gave a significantly better fit to the calculated probability distribution than any other continuous distribution.

On the basis of these considerations, we obtained estimated uncertainties in inhalation doses for each exposure situation of concern by representing all parameters in Table 4-15 by lognormal probability distributions and combining (multiplying) the probability distributions of each parameter. This approach facilitates ease of calculations and transparency of the results. This approach also can be justified on the grounds that: (1) assumed probability distributions of all parameters that contribute to the results in Table 4-15 represent subjective judgments about 90% credibility intervals and the shapes of distributions, rather than results of a rigorous statistical analysis of relevant data, which are lacking for most parameters; and (2) results of this analysis are used to derive effective resuspension factors, which are highly uncertain, to the nearest power of 10 only, and more precise estimates are not needed.

### **4.2.2** *Probability Distributions of Dose from Inhalation of Fission and Activation Products*

In assessing uncertainties in estimated doses from inhalation of mixtures of fission and activation products in previously deposited fallout that was resuspended by nuclear detonations at NTS, we distinguished between intakes of small, respirable particles and larger, nonrespirable particles. This distinction was based on the considerations that (1) the effects of fractionation of fission and activation products and its uncertainty on inhalation doses depend on particle size (i.e., whether or not resuspended fallout particles were respirable), (2) the nonrespirable fraction of inhalable radionuclides in resuspended fallout should have been substantially larger than the

[58] Continuous probability distributions that can be specified in Crystal Ball® include normal, triangular, poisson, binomial, lognormal, uniform, exponential, geometric, Weibull, beta, hypergeometric, gamma, logistic, pareto, extreme value, negative binomial, log-triangular, and log-uniform.

respirable fraction, and (3) there could be a substantial bias in ICRP's current dose coefficients for inhalation of radionuclides in nonrespirable form that results in overestimates of dose in resuspension scenarios of concern, but it is less likely that there is a substantial bias in ICRP's dose coefficients for inhalation of radionuclides in respirable form (see Sections 4.1.2.4.1, 4.1.3.2, and 4.1.5.4.3; Tables 4-1, 4-7, and 4-14).

Estimated uncertainties in doses from inhalation of fission and activation products in fallout that was resuspended in the thermal-pulse or blast wave region of nuclear detonations at NTS obtained in this analysis are summarized in Table 4-16 as medians and 90% credibility intervals of lognormal probability distributions. These distributions are relative to the concentrations of fission and activation products in fallout at NTS that are assumed in dose reconstructions and relative to dose coefficients for specific organs or tissues from inhalation of radionuclides in respirable or nonrespirable form by adult members of the public that are currently recommended by ICRP. They are intended to apply to any organ or tissue and any mixture of fission and activation products in resuspended fallout (i.e., at any time after a previous detonation that resulted in fallout at NTS).

Results in Table 4-16 indicate that the probability distributions of dose from inhalation of fission and activation products in respirable or nonrespirable form do not differ greatly. The uncertainty is slightly larger for respirable particles, because the uncertainty in the respirable fraction of inhalable particles (see Table 4-7) is larger than the uncertainty in the bias in ICRP's dose coefficients, which is assumed to apply only to nonrespirable particles (see Table 4-14). The contributions to estimated uncertainties in doses from inhalation of fission and activation products in respirable or nonrespirable form in the thermal-pulse and blast-wave regions, as well as GSDs of the assumed lognormal probability distributions, are as follows:

Thermal-pulse region, respirable (nonrespirable) particles [GSD = 16 (14)] –

Resuspension factor, 65% (58%)

Dose coefficients, 26% (30%)

Concentrations on ground surface, 8% (10%)

Breathing rate, 2% (2%)

Blast-wave region, respirable (nonrespirable) particles [GSD = 38 (33)] –

Resuspension factor, 80% (76%)

Dose coefficients, 15% (17%)

Concentrations on ground surface, 5% (6%)

Breathing rate, 1% (1%)

The most important contributors to the estimated uncertainties in inhalation doses are the assumed uncertainties in the resuspension factor and dose coefficients; assumed uncertainties in the concentrations of fission and activation products in fallout on the ground surface and the breathing rate are minor contributors. Thus, parameter uncertainties that are the most important in determining uncertainties in doses from inhalation of resuspended fission and activation products are the assumed uncertainties in the resuspension factor that applies to all fallout on the ground surface and the inhalable fraction of resuspended radionuclides (see Table 4-7) and the assumed uncertainty in dose coefficients due to uncertainties in ICRP's recommended dosimetric and biokinetic models (see Table 4-14).

### **4.2.3** *Probability Distributions of Dose from Inhalation of Plutonium*

The analysis of uncertainty in estimated doses from inhalation of plutonium in previously deposited fallout that was resuspended by nuclear detonations at NTS is similar to the analysis for mixtures of fission and activation products described in the previous section. The only difference is that the effects of fractionation and its uncertainty on doses from inhalation of plutonium do not depend on particle size; i.e., those effects are the same for plutonium in respirable or nonrespirable form (see Section 4.1.2.4). This difference has little effect on comparisons of estimated uncertainties in doses from inhalation of fission and activation products and inhalation of plutonium.

Estimated uncertainties in doses from inhalation of plutonium in fallout that was resuspended in the thermal-pulse or blast-wave region of nuclear detonations at NTS obtained in this analysis are summarized in Table 4-17 as medians and 90% credibility intervals of

lognormal probability distributions. These distributions are relative to the concentrations of plutonium in fallout at NTS that are assumed in dose reconstructions and relative to dose coefficients for specific organs or tissues from inhalation of plutonium in respirable or nonrespirable form by adult members of the public that are currently recommended by ICRP. They are intended to apply to any organ or tissue.

Results in Table 4-17 indicate that the probability distributions of dose from inhalation of plutonium in respirable or nonrespirable form do not differ greatly, as is the case in the results for fission and activation products; the uncertainty again is slightly larger for respirable particles. The contributions to estimated uncertainties in doses from inhalation of plutonium in respirable or nonrespirable form in the thermal-pulse and blast-wave regions, as well as GSDs of the assumed lognormal probability distributions, are as follows:

Thermal-pulse region, respirable (nonrespirable) particles [GSD = 23 (22)] –

Resuspension factor, 48% (41%)

Dose coefficients, 44% (51%)

Concentrations on ground surface, 6% (7%)

Breathing rate, 2% (2%)

Blast-wave region, respirable (nonrespirable) particles [GSD = 51 (50)] –

Resuspension factor, 68% (63%)

Dose coefficients, 27% (32%)

Concentrations on ground surface, 4% (4%)

Breathing rate, 1% (1%)

As in the analysis for fission and activation products, the most important contributors to the estimated uncertainties in inhalation doses are the assumed uncertainties in the resuspension factor and dose coefficients; assumed uncertainties in the concentrations of plutonium in fallout on the ground surface and the breathing rate are minor contributors. However, for inhalation of plutonium in nonrespirable form in the thermal-pulse region, the uncertainty in dose coefficients is more important than the uncertainty in the resuspension factor. The greater importance of the

uncertainty in dose coefficients for plutonium compared with the importance of that uncertainty for fission and activation products is a result of the assumptions of a larger uncertainty in ICRP's dosimetric and biokinetic models for plutonium and, in the case of inhalation of nonrespirable particles, a larger uncertainty in the bias in ICRP's dose coefficients (see Table 4-14). Thus, as in the case of fission and activation products, parameter uncertainties that are the most important in determining uncertainties in doses from inhalation of resuspended plutonium are the assumed uncertainties in the resuspension factor that applies to all fallout on the ground surface and the inhalable fraction of resuspended radionuclides (see Table 4-7) and the assumed uncertainty in dose coefficients due to uncertainties in ICRP's recommended dosimetric and biokinetic models (see Table 4-14).

### **4.2.4** *Comparison of Results for Fission/Activation Products and Plutonium*

A comparison of the results of our analysis of uncertainty in estimated doses from inhalation of fission and activation products in Table 4-16 with the corresponding results for plutonium in Table 4-17 indicates that estimated uncertainties are larger for plutonium. The larger uncertainties for plutonium are due primarily to an assumption of a larger uncertainty in ICRP's dosimetric and biokinetic models for plutonium (a factor of 30, compared with a factor of 10 for fission and activation products). Consequently, at the upper 95% credibility limit ($95^{th}$ percentile), estimated doses from inhalation of plutonium are higher than estimated doses from inhalation of fission and activation products. The $95^{th}$ percentiles differ by a factor of 3 for respirable and nonrespirable forms in both regions.

The comparison summarized above indicates that the results for plutonium are more relevant in deriving point values of effective resuspension factors that should be assumed in dose reconstructions to ensure that estimates of inhalation dose due to resuspension of fallout in the thermal-pulse or blast-wave region of a nuclear detonation at NTS provide credible upper bounds (at least 95% credibility limits) of possible doses. More specifically, the $95^{th}$ percentiles of the probability distributions of doses from inhalation of plutonium in nonrespirable form are the

relevant quantities that should be used in deriving effective resuspension factors that apply in the thermal-pulse or blast-wave region. These resuspension factors are derived in Section 5.

### **4.2.5** *Consideration of Parameter Correlations*

With one exception, the analysis of uncertainties in estimated inhalation doses presented in this report and summarized in Tables 4-16 and 4-17 assumes that there are no correlations among different parameters that contribute to uncertainties in estimated concentrations of radionuclides on the ground surface, resuspension factors, the breathing rate, and dose coefficients for inhalation. The one exception, which is described in Section 4.1.3.2, is that the respirable and nonrespirable fractions of resuspended radionuclides in inhalable form are perfectly correlated by requiring that their sum is unity.

In this section, possible parameter correlations and their potential effects on estimated uncertainties in inhalation doses and, therefore, the derivation of effective resuspension factors are considered. Two possibilities noted previously are a correlation between the degree of fractionation of radionuclides in fallout at NTS and the fraction of resuspended radionuclides in inhalable form (see Section 4.1.2.4.1, footnote 20) and a correlation between the respirable and nonrespirable fractions of radionuclides in inhalable form and the inhalable fraction of resuspended radionuclides (see Section 4.1.3.2.6). Another possibility is a correlation between the degree of fractionation of radionuclides in fallout and the bias in dose coefficients recommended by ICRP—i.e., the greater the degree of fractionation, the more likely it could be that ICRP's dose coefficients overestimate values that apply to radionuclides in fallout. There should not be any correlations that involve measured or calculated exposure rates in air from radionuclides deposited on the ground surface, the shielding effect of ground roughness, and the resuspension factor that applies to all radionuclides on the ground surface. In addition, by including a parameter to account for a possible bias in applying ICRP's dose coefficients to inhalation of radionuclides in fallout, uncertainties in ICRP's dosimetric and biokinetic models are considered to be independent of the degree of fractionation and are uncorrelated with any other parameter.

As noted in the previous section, estimated uncertainties in doses from inhalation of resuspended plutonium in nonrespirable form that were obtained in this analysis provide the limiting cases that should be used in deriving effective resuspension factors in the thermal-pulse and blast-wave regions. Therefore, we consider possible parameter correlations and their effects for those cases only.

The fraction of resuspended plutonium in inhalable form and the bias in ICRP's dose coefficients for inhalation of plutonium in nonrespirable form both should be negatively correlated with the degree of fractionation of radionuclides (enhancement of plutonium) in fallout at NTS—i.e., the greater the degree of fractionation, the smaller the fraction of resuspended plutonium in inhalable form and the smaller the equivalent doses per unit activity intake of plutonium relative to ICRP's dose coefficients—essentially because an increase in the degree of fractionation should result in an increase in the fraction of larger particles (see Section 4.1.2.4). Increases in the fraction of larger particles should reduce the fraction of resuspended plutonium in inhalable form and should weight the particle-size distribution of the inhalable fraction more toward larger particles. The latter effect should increase the tendency for ICRP's dose coefficients to overestimate doses from inhalation of plutonium in nonrespirable form when fallout particles are expected to be insoluble, plutonium is expected to be distributed mainly in the volume of fallout particles, and some of the energy of emitted alpha particles would be absorbed in the particles (see Sections 4.1.5.2 and 4.1.5.4.2). If the fraction of resuspended plutonium in inhalable form and the bias in ICRP's dose coefficients for inhalation of plutonium are negatively correlated with the degree of fractionation, those two parameters would be positively correlated—i.e., the smaller the fraction of resuspended plutonium in inhalable form, the greater the reduction in inhalation doses compared with doses calculated using ICRP's dose coefficients.

In considering a possible correlation between the nonrespirable fraction of resuspended plutonium in inhalable form and the inhalable fraction of resuspended plutonium, we assume that the more the particle-size distribution of plutonium is weighted toward larger particles, the higher the nonrespirable fraction of inhalable plutonium would be. Arguments presented above then indicate that such a correlation should result in a positive correlation between the degree of

enhancement of plutonium in fallout at NTS and the nonrespirable fraction of inhalable plutonium. However, there is little evidence of a positive correlation between the nonrespirable fraction of inhalable plutonium and the inhalable fraction of plutonium in fallout at NTS in the limited data discussed in Sections 4.1.3.2.5 and 4.1.3.2.6.

To investigate potential effects of the correlations described above, we performed two calculations using Crystal Ball® (Decisioneering, 2001). In the first calculation, we combined assumed probability distributions of the enhancement of plutonium in fallout at NTS due to fractionation (see Table 4-1), the inhalable fraction of resuspended plutonium (see Table 4-7), and the bias in ICRP's dose coefficients for inhalation of plutonium in nonrespirable form (see Table 4-14) by assuming a perfect negative correlation between the enhancement due to fractionation and the other two parameters (i.e., a correlation coefficient of −1). This assumption maximizes the effect of correlations. As noted above, these assumptions imply a perfect positive correlation (correlation coefficient of +1) between the inhalable fraction of resuspended plutonium and the bias in ICRP's dose coefficients. In the second calculation, we used the same assumptions as in the first calculation and included the nonrespirable fraction of resuspended plutonium in inhalable form (see Table 4-7) by assuming that it is perfectly positively correlated with the enhancement of plutonium due to fractionation.

In each calculation, we compared the 95$^{th}$ percentile of the resulting probability distribution with the 95$^{th}$ percentile that was obtained by assuming that all parameters are uncorrelated. In both calculations, the 95$^{th}$ percentile increased when the correlations described above were included. However, the increase was only about 10%. The slight increase in the 95$^{th}$ percentile in both calculations indicates that the assumed positive correlation between the inhalable fraction of resuspended plutonium and the bias in ICRP's dose coefficients is more important than the assumed negative correlation between the enhancement of plutonium due to fractionation and the inhalable fraction of resuspended plutonium. The assumed positive correlation between the enhancement of plutonium and the nonrespirable fraction of resuspended plutonium in inhalable form in the second calculation had virtually no effect, because the uncertainty in the latter parameter is very small (see Section 4.1.3.2.6). The small effects of the assumed parameter correlations in these calculations are not surprising when the uncertainty in

one parameter (the inhalable fraction of resuspended plutonium) is much larger than uncertainties in all other parameters.

When uncertainties in other parameters that are not correlated with the enhancement of plutonium in fallout due to fractionation, including the resuspension factor that applies to all fallout on the ground surface and ICRP's dose coefficients, are large (i.e., a factor of 10 or more), it is evident from the calculations described above that any parameter correlations that might be considered would have a negligible effect on estimated upper 95% credibility limits of inhalation doses. Therefore, it is not important to account for possible parameter correlations of the kind described above in this analysis.

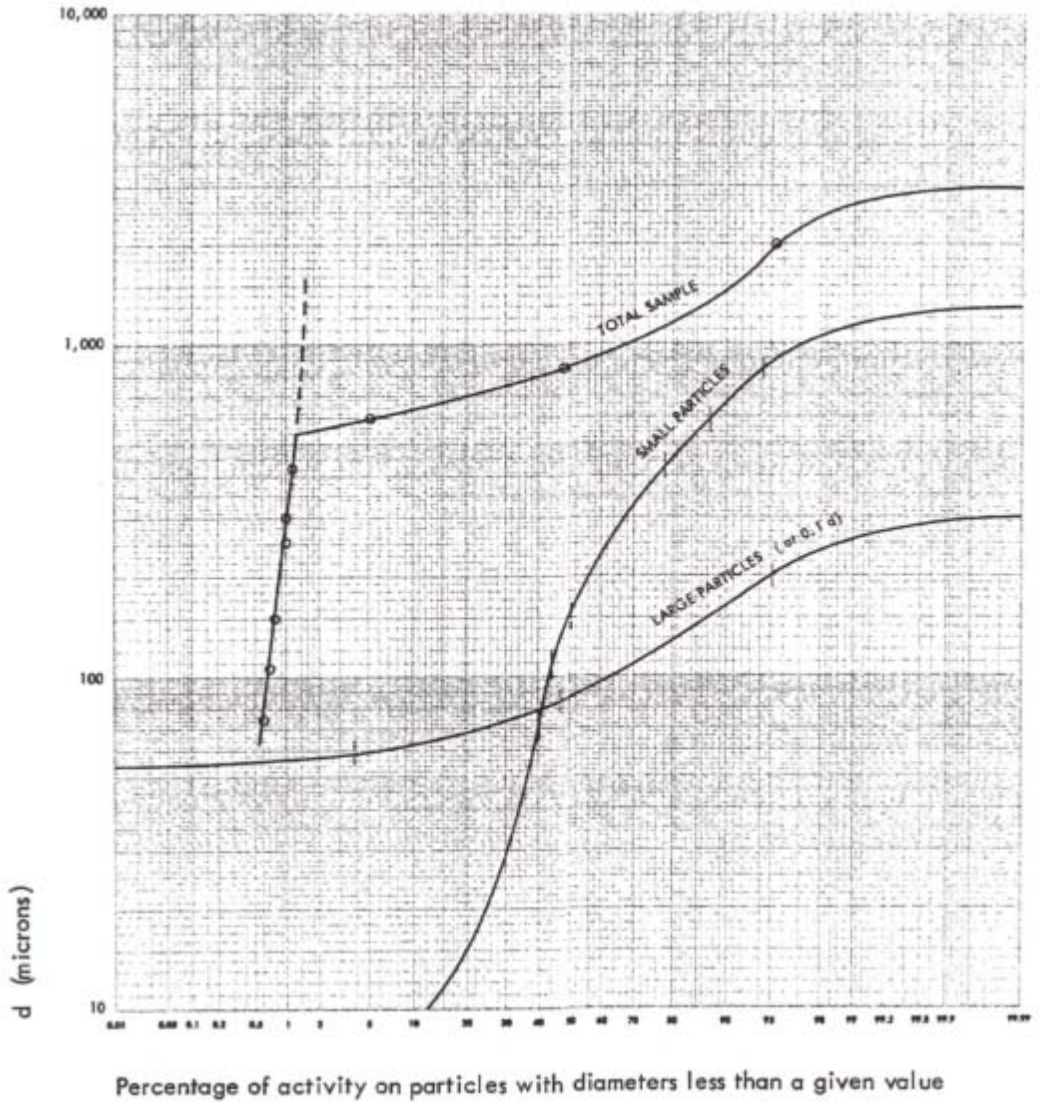


**Figure 4-1.** Distribution of activity with particle diameter in fallout sample at distance of 1.1 miles from ground zero at Shot DIABLO in Operation PLUMBBOB at NTS (Miller, 1969; Figure 8). Activity distribution of large particles is shown at one-tenth of actual particle diameter.

**Table 4-1.** Summary of assumed uncertainties in estimates of concentrations of radionuclides in fallout deposited on ground surface at NTS[a]

| Source of uncertainty[b] | Probability distribution |
|---|---|
| Estimation of photon exposure rates in air above ground at times and locations of exposure based on measurements at various times and locations after each detonation[c] | Lognormal distribution with median at 1.0 and 90% credibility interval between 0.33 and 3.0 |
| Calculation of exposure rates from infinite, uniformly contaminated plane source | Normal distribution with 90% credibility interval between 0.8 and 1.2 |
| Reductions in calculated exposure rates due to finite extent of source region | Reductions and their uncertainty are assumed to be negligible |
| Shielding effect of ground roughness[d] | Uniform distribution with minimum at 0.78 and maximum at 1.4 |
| Effects of fractionation of radionuclides in fallout on estimates of inhalation dose[e] | |
| Fission and activation products | |
| Inhalation of respirable particles | Uniform distribution between 0.5 and 1.9 |
| Inhalation of nonrespirable particles[f] | Uniform distribution between 0.2 and 1.7 |
| Plutonium – Inhalation of respirable and nonrespirable particles | Uniform distribution between 1.0 and 3.3 |

[a] Analysis of uncertainties is described in Sections 4.1.1 and 4.1.2. Resulting uncertainties in activity concentrations of fission and activation products or plutonium in fallout deposited on ground surface are summarized in Section 4.1.2.5 and Table 4-15.

[b] Unless otherwise noted, uncertainties apply to all radionuclides in fallout.

[c] Uncertainty is relative to point estimates that are assumed in dose reconstructions for military participants.

[d] Probability distribution modifies shielding effect of ground roughness of 0.7 that is assumed in dose reconstructions for military participants (Egbert et al., 1985; Raine et al., 2007).

[e] Probability distributions assume that fallout at NTS was enhanced in refractory radionuclides compared with unfractionated mixtures of refractory and volatile radionuclides.

[f] When inhalation of nonrespirable particles is assumed, inhalation doses can be estimated using dose coefficients for ingestion that are adjusted to account for fraction of inhaled material that is swallowed.

**Table 4-2.** Summary of reported resuspension factors associated with mechanical stresses at sites where nuclear weapons were tested[a]

| Location | Source material | Resuspension stress/ measurement conditions | Resuspension factor ($m^{-1}$) |
|---|---|---|---|
| Maralinga, Australia[b] | Fallout | Road survey at 1−2 d | $< 1 \times 10^{-8} - > 2 \times 10^{-6}$ |
| | | Cab of landrover, 5th h | $6.4 \times 10^{-5}$ |
| | | Cab of landrover, 8th h | $2.5 \times 10^{-5}$ |
| | Uranium | Dust stirred at height of 0.3 m | $1 \times 10^{-3}$ |
| | Plutonium | Vehicle dust at height of 0.3 m | $3 \times 10^{-7} - 7 \times 10^{-4}$ |
| | | Pedestrian dust at height of 0.3 m | $1.5 \times 10^{-6} - 3 \times 10^{-4}$ |
| Nevada Test Site[c] | Plutonium | Extensive vehicular traffic | $7 \times 10^{-5}$ |
| Monte Bello Islands, Australia[b] | Fallout | Road survey from back of landrover, | |
| | | 4th d | $8 \times 10^{-7} - 3 \times 10^{-5}$ |
| | | 7th d | $7 \times 10^{-7} - 4 \times 10^{-6}$ |
| | | At tailboard, 7th d | $1.6 \times 10^{-5} - 3.1 \times 10^{-5}$ |
| Emu Field, Australia[b] | Fallout gamma | Walking survey | $3 \times 10^{-7}$ |
| | | Vehicle survey, at tailboard | $2 \times 10^{-6}$ |

[a] Data summarized in Table 12.9 of Sehmel (1984); resuspension factors are presumed to apply at height of 1 m above ground, except as noted. Data on resuspension factors associated with wind stresses summarized in Table 12.7 of Sehmel (1984) are discussed in Section 4.1.3.1.2.

[b] Data reported by Stewart (1967).

[c] Data reported by Langham (1971).

**Table 4-3.** Percentages of total activities in smallest size fractions of fallout samples from tower shots in Operation UPSHOT-KNOTHOLE at NTS[a]

| Shot | Distance (miles)[b] | Exposure rate (mR $h^{-1}$)[c] | Particle size (μm) | | | |
|---|---|---|---|---|---|---|
| | | | 0−5 | 5−44[d] | 44−88 | 88−125 |
| NANCY | **3.5** | | | **22.3** | **22.7** | **19.0** |
| | 12 | $1.8 \times 10^2$ | | 7.9 | 0.6 | 0.5 |
| | 19.5 | $1.5 \times 10^2$ | | 2.4 | 1.2 | 0.7 |
| BADGER | **~ 3** | **$1.1 \times 10^2$** | **0.3** | **3.1** | **2.5** | **8.8** |
| | 16.5 | $3.2 \times 10^1$ | 0.6 | 3.8 | 1.9 | 0.7 |
| | 16.6 | $1.0 \times 10^3$ | | 1.5 | 0.3 | 1.9 |
| | 16.6 | $9.0 \times 10^2$ | 2.4 | 3.4 | 2.3 | 1.7 |
| | 17.5 | $7.7 \times 10^2$ | 0.7 | 1.2 | 1.4 | 0.7 |
| | 18.5 | $3.3 \times 10^1$ | 1.1 | 0.9 | 4.0 | 3.9 |
| SIMON | **~ 3** | | | **0.01** | **0.03** | **0.8** |
| | 14.7 | $5.2 \times 10^2$ | 0.2 | 2.9 | 5.0 | 1.0 |
| | 14.7 | $1.6 \times 10^3$ | 0.3 | 2.5 | 4.9 | 1.9 |
| | 16.8 | 4.2 | | 49.2 | 34.8 | 5.7 |
| | 17.4 | 2.5 | | 43.6 | 14.5 | 15.5 |

[a] Data at distances from ground zero to 20 miles obtained from Tables 3.1, 3.5, and 3.10 of Rainey et al. (1954); heights of detonation and yields are described in Section 4.1.3.2.2. Data in **bold face** denote measurements within boundary of NTS.

[b] Distance from ground zero at which fallout was collected.

[c] Exposure rate at time after detonation of 12 hours.

[d] Data apply to 0−44 μm size fraction when value for 0−5 μm size fraction is omitted; in those cases, quantities of material in 0−5 μm size fraction were insufficient for separation.

**Table 4-4**. Percentages of total activities in smallest size fractions of fallout samples from tower shots in Operation TEAPOT at NTS[a]

| Shot | Distance (miles)[b] | Activity (μCi ft$^{-2}$)[c] | Particle sizes (μm) | | | | |
|---|---|---|---|---|---|---|---|
| | | | 0–5 | 5–20 | 20–44 | 44–88 | 88–125 |
| TESLA | 12 | $6.3 \times 10^{1}$ | 4.2 | 4.0 | 0.84 | 22.9 | 64.9 |
| | | $8.6 \times 10^{1}$ | 4.0 | 0.88 | 0.31 | 6.1 | 80.1 |
| | | $3.7 \times 10^{2}$ | 3.4 | 1.9 | 0.09 | 5.0 | 70.2 |
| | | $1.1 \times 10^{3}$ | 3.0 | 0.32 | 0.08 | 4.9 | 47.3 |
| | | $8.4 \times 10^{2}$ | 2.1 | 1.2 | 0.20 | 4.5 | 48.8 |
| | | $2.7 \times 10^{3}$ | 1.7 | 0.19 | 0.12 | 3.6 | 5.5 |
| | | $4.3 \times 10^{3}$ | 0.27 | 0.07 | 0.03 | 3.1 | 3.0 |
| | | $4.8 \times 10^{3}$ | 1.7 | 0.58 | 0.05 | 1.9 | 1.8 |
| | | $2.0 \times 10^{3}$ | 1.7 | 2.0 | 0.12 | 2.1 | 1.5 |
| | | $1.5 \times 10^{3}$ | 2.4 | 0.49 | 0.04 | 2.9 | 4.2 |
| | | $5.7 \times 10^{1}$ | 2.6 | 6.9 | 0.27 | 17.5 | 11.2 |
| | | 9.5 | 27.5 | 19.6 | 0.70 | 22.0 | 18.5 |
| TURK | 11.5 | $8.7 \times 10^{2}$ | 6.7 | 4.4 | 0.14 | 4.7 | 6.1 |
| | | $1.4 \times 10^{3}$ | 10.4 | 2.2 | 0.38 | 4.2 | 6.1 |
| | | $1.9 \times 10^{3}$ | 9.9 | 4.7 | 0.35 | 4.3 | 3.7 |
| | | $1.2 \times 10^{3}$ | 4.3 | 0.57 | 0.68 | 2.3 | 17.3 |
| APPLE I | 13 | $7.1 \times 10^{2}$ | 0.02 | 0.88 | 0.40 | 4.2 | 1.0 |
| | | $1.1 \times 10^{3}$ | 4.9 | 6.6 | 1.2 | 3.0 | 0.42 |
| | | $9.2 \times 10^{2}$ | 5.3 | 4.2 | 0.95 | 1.4 | 0.84 |

Table is continued on following page; see end of table for footnotes.

**Table 4-4**. (continued)

| Shot | Distance (miles)[b] | Activity (μCi ft$^{-2}$)[c] | Particle sizes (μm) | | | | |
|---|---|---|---|---|---|---|---|
| | | | 0–5 | 5–20 | 20–44 | 44–88 | 88–125 |
| MET | 20 | $1.9 \times 10^{1}$ | 16.4 | 8.3 | 5.6 | 8.6 | 6.1 |
| | | $1.5 \times 10^{1}$ | 9.6 | 15.9 | 15.0 | 19.7 | 12.0 |
| | | $2.3 \times 10^{2}$ | 15.7 | 13.0 | 2.6 | 1.8 | 6.2 |
| | | $6.7 \times 10^{2}$ | 6.0 | 9.5 | 1.6 | 2.4 | 1.1 |
| | | $2.6 \times 10^{3}$ | 2.8 | 4.1 | 0.46 | 1.5 | 0.47 |
| | | $4.4 \times 10^{3}$ | 2.6 | 2.1 | 0.20 | 1.7 | 0.66 |
| | | $5.5 \times 10^{3}$ | 3.8 | 0.90 | 0.29 | 1.4 | 0.53 |
| | | $3.9 \times 10^{3}$ | 0.0 | 0.20 | 0.42 | 1.1 | 0.50 |
| | | $1.8 \times 10^{3}$ | 4.3 | 1.9 | 0.79 | 2.0 | 0.01 |
| | | $3.0 \times 10^{3}$ | 3.1 | 0.95 | 0.62 | 2.0 | 1.4 |
| | | $1.3 \times 10^{3}$ | 0.79 | 0.20 | 0.07 | 0.05 | 0.33 |
| | | $2.6 \times 10^{2}$ | 4.8 | 7.0 | 1.9 | 4.9 | 1.4 |
| | | 8.7 | 9.3 | 22.0 | 4.9 | 33.3 | 10.2 |
| APPLE II | **7** | **$1.3 \times 10^{3}$** | **0.32** | **0.22** | **0.02** | **0.54** | **0.01** |
| | | **$4.4 \times 10^{3}$** | **0.52** | **0.31** | **0.10** | **0.48** | **0.20** |
| | | **$5.9 \times 10^{3}$** | **0.36** | **0.12** | **0.08** | **0.33** | **0.18** |
| | | **$1.2 \times 10^{3}$** | **1.3** | **1.1** | **0.10** | **0.59** | **0.28** |
| | | **$2.1 \times 10^{3}$** | **0.08** | **0.05** | **0.02** | **0.09** | **0.04** |
| | | **$7.6 \times 10^{2}$** | **0.10** | **0.10** | **0.14** | **0.65** | **0.36** |
| | | **$7.5 \times 10^{1}$** | **0.85** | **0.0** | **0.0** | **2.2** | **0.0** |

[a] Data at distances from ground zero to 20 miles obtained from Tables C.1, D.1, E.1, F.1, and G.1 of Baurmash et al. (1958); heights of detonation and yields are described in Section 4.1.3.2.2. Data at Shot APPLE II at location where total activity was $2.5 \times 10^{3}$ μCi ft$^{-2}$ are omitted because reported activity in each size fraction up to 500 μm was identical to corresponding value at location where total activity was $4.4 \times 10^{3}$ μCi ft$^{-2}$ but total activity in all size fractions was less than 100%. Data in **bold face** denote measurements within boundary of NTS.

[b] Distance from ground zero at which fallout was collected.

[c] Areal concentration of total activity at time after detonation of 12 hours.

**Table 4-5.** Percentages of total activities in smallest size fractions of on-site fallout samples from tower Shot SHASTA in Operation PLUMBBOB at NTS[a]

| Distance (miles)[b] | Total activity[c] | Particle sizes (μm) | | | |
|---|---|---|---|---|---|
| | | 0–43 | 43–74 | 74–104 | 104–146 |
| 2.2 | 398 | 0.29 | 0.15 | 0.10 | 0.16 |
| 2.5 | 6.2 | 1.4 | 1.1 | 0.31 | 0.31 |
| 2.5 | 23.6 | 2.1 | 2.6 | 1.5 | 1.1 |
| 2.5 | 635 | 0.22 | 0.18 | 0.09 | 0.17 |
| 3.1 | 1,080 | 0.09 | 0.20 | 0.13 | 0.24 |
| 4.2 | 1,870 | 0.38 | 0.19 | 0.09 | 0.11 |
| 4.7 | 1,480 | 0.37 | 0.20 | 0.17 | 0.01 |

[a] Data obtained from Table 16 of Miller (1969) apply to magnetic and nonmagnetic particles combined; height of detonation and yield are described in Section 4.1.3.2.2.

[b] Distance from ground zero at which fallout was collected.

[c] Value multiplied by $10^{12}$ gives estimated number of fissions in all particle sizes.

**Table 4-6.** Percentages of total activities in size fractions of 0−104 μm magnetic particles in on-site fallout samples from tower Shot SHASTA in Operation PLUMBBOB at NTS[a]

| Distance (miles)[b] | Total activity[c] | Percent magnetic[d] | Particle sizes (μm) | | | | |
|---|---|---|---|---|---|---|---|
| | | | 0–10 | 10–20 | 20–43 | 43–74 | 74–104 |
| 2.2 | 398 | 93 | – | 0.027 | 0.16 | 0.15 | 0.11 |
| 2.5 | 635 | 93 | 0.002 | 0.019 | 0.12 | 0.18 | 0.16 |
| 3.1 | 1,080 | 99.6 | – | 0.001 | 0.041 | 0.15 | 0.16 |
| 4.2 | 1,870 | 99.5 | – | 0.086 | 0.19 | 0.17 | 0.13 |
| 4.7 | 1,480 | 99.7 | 0.019 | 0.084 | 0.20 | 0.19 | 0.13 |

[a] Data obtained from Table 17 of Miller (1969); height of detonation and yield are described in Section 4.1.3.2.2.

[b] Distance from ground zero at which fallout was collected.

[c] Value multiplied by $10^{12}$ gives estimated number of fissions in magnetic and nonmagnetic particles combined in all particle sizes.

[d] Percentage of total activity in all particle sizes that was contained in magnetic particles.

**Table 4-7.** Summary of assumed uncertainties in parameters to estimate resuspension factors that apply to respirable or nonrespirable radionuclides in inhalable form in thermal-pulse and blast-wave regions near nuclear detonations at NTS[a]

| Parameter | Probability distribution |
|---|---|
| Resuspension factor that applies to all previously deposited fallout | |
| Thermal-pulse region | Lognormal distribution with median at $10^{-3}$ $m^{-1}$ and 90% credibility interval between $10^{-4}$ and $10^{-2}$ $m^{-1}$ |
| Blast-wave region | Lognormal distribution with median at $10^{-5}$ $m^{-1}$ and 90% credibility interval between $10^{-7}$ and $10^{-3}$ $m^{-1}$ |
| Inhalable fraction of resuspended radionuclides[b] | Lognormal distribution with median at 0.01 and 90% credibility interval between 0.001 and 0.1 |
| Respirable fraction of resuspended radionuclides in inhalable form[c] | Log-triangular distribution with minimum at ($ln$ 0.01) = −4.6, mode at ($ln$ 0.3) = −1.2, and maximum at ($ln$ 1.0) = 0[d] |
| Nonrespirable fraction of resuspended radionuclides in inhalable form | Calculated from requirement that sum of respirable and nonrespirable fractions of resuspended radionuclides in inhalable form must be unity[e] |

[a] Thermal-pulse and blast-wave regions are described in Section 2, and analysis of uncertainties in resuspension factors is presented in Section 4.1.3. Resulting uncertainties in resuspension factors for radionuclides in respirable form or inhalable radionuclides in nonrespirable form in thermal-pulse and blast-wave regions are summarized in Section 4.1.3.3 and Table 4-15.

[b] Inhalable fraction is assumed to be the fraction of the activity of resuspended radionuclides in particles of diameter 44 μm or less (see Section 4.1.3.2.4). Larger particles of diameter up to 100 μm also would be inhalable, but such particles should not have remained airborne for significant periods of time during exposures of military participants in thermal-pulse or blast-wave region.

[c] Particles of diameter less than 10 μm are assumed to be respirable.

[d] Lower bound, most probable value (mode), and upper bound of probability distribution are assumed to be 0.01, 0.3, and 1.0, respectively; median of distribution is 0.17, mean is 0.22, and 90% credibility interval ranges from 0.024 to 0.59.

[e] Requirement ensures that correlation between respirable and nonrespirable fractions of resuspended radionuclides in inhalable form is preserved when those fractions are described by probability distributions. Resulting probability distribution has lower bound, most probable value, and upper bound at 0, 0.7, and 0.99, respectively; median of distribution is 0.83, mean is 0.78, and 90% credibility interval ranges from 0.41 to 0.98.

**Table 4-8.** Estimates by NCRP of reliability of effective dose coefficients for intakes of radionuclides relative to values calculated by ICRP[a]

| Radionuclide | Route of intake[b] | Uncertainty factor[c] |
|---|---|---|
| High reliability | | |
| $^{3}H$ (HTO) | Ingestion | 2 |
| $^{14}C$ ($CO_2$) | Inhalation | 2 |
| $^{137}Cs$ | Inhalation or ingestion | 2 |
| $^{90}Sr$ | Inhalation or ingestion | 3 |
| $^{131}I$ | Inhalation or ingestion | 3 |
| $^{140}La$ | Ingestion | 3 |
| Intermediate reliability | | |
| $^{14}C$ ($CO_2$) | Ingestion | 5 |
| $^{55}Fe$, $^{95}Nb$ | Inhalation or ingestion | 5 |
| $^{60}Co$, $^{144}Ce$ | Inhalation | 5 |
| $^{140}Ba$, $^{226}Ra$ | Inhalation or ingestion | 5 |
| $^{140}La$, $^{210}Po$ | Inhalation | 5 |
| $^{210}Pb$, $^{230}Th$ | Inhalation | 5 |
| $^{234}U$ | Inhalation | 5 |
| Low reliability | | |
| $^{60}Co$, $^{210}Pb$ | Ingestion | 10 |
| $^{95}Zr$, $^{106}Ru$ | Inhalation or ingestion | 10 |
| $^{125}Sb$ | Inhalation or ingestion | 10 |
| $^{144}Ce$ | Ingestion | 10 |
| $^{210}Po$ | Ingestion | 10 |
| $^{230}Th$, $^{234}U$ | Ingestion | 10 |
| $^{237}Np$, $^{239}Pu$ | Inhalation or ingestion | 10 |
| $^{241}Am$, $^{244}Cm$ | Inhalation or ingestion | 10 |

[a] Estimates of reliability obtained from NCRP (1998; Table 8.2) and Bouville et al. (1994) apply to effective dose equivalents per unit activity intake in healthy adult males calculated using dosimetric and biokinetic models recommended in ICRP Publication 30 (ICRP, 1979).

[b] Inhaled material is assumed to be in form of respirable particles with AMAD of 1 μm, except $^{3}H$ (HTO) and $^{14}C$ ($CO_2$) are assumed to be in vapor and gaseous form, respectively.

[c] Ratio of upper 95% credibility limit of subjective probability distribution of effective dose coefficient to value calculated by ICRP.

**Table 4-9.** Uncertainty categories in assessment of uncertainties in risk coefficients for intakes of radionuclides in the environment in EPA's current federal guidance[a]

| Uncertainty category | Definition[b] | Uncertainty factor[c] | % radionuclides in each category[d] | |
|---|---|---|---|---|
| | | | Inhalation | Ingestion |
| A | $Q_{95}/Q_5 < 15$ | ≈ 4 or less | 42 | 26 |
| B | $15 \leq Q_{95}/Q_5 < 35$ | ≈ 4–6 | 42 | 51 |
| C | $35 \leq Q_{95}/Q_5 < 65$ | ≈ 6–8 | 10 | 11 |
| D | $65 \leq Q_{95}/Q_5 < 150$ | ≈ 8–12 | 5 | 8 |
| E | $Q_{95}/Q_5 \geq 150$ | ≈ 12 or greater | 1 | 3 |

[a] Uncertainty categories and associated ranges of uncertainty in risk coefficients for radionuclides in EPA's Federal Guidance Report No. 13 (Eckerman et al., 1999) as given by Pawel et al. (2007; Table 4). Risk coefficients give cancer risks per unit activity intake by inhalation or ingestion in a population of all ages, and uncertainties take into account uncertainties in risk models for specific organs or tissues and uncertainties in ICRP's recommended dosimetric and biokinetic models for inhalation or ingestion of radionuclides by members of the public (ICRP, 1996a; 2002).

[b] $Q_{95}$ and $Q_5$ denote upper 95% and lower 5% credibility limits, respectively, that were judged by EPA to define range of credible values (90% credibility interval) of risk coefficient.

[c] Uncertainty factor calculated as $(Q_{95}/Q_5)^{½}$ is intended to represent ratio of upper 95% credibility limit of risk coefficient to median.

[d] Uncertainty categories for all radionuclides considered in Federal Guidance Report No. 13 are given in Tables D-1 and D-2 of Pawel et al. (2007).

**Table 4-10.** Estimates of uncertainty in risk coefficients for intakes of selected radionuclides in the environment in EPA's current federal guidance[a]

| Route of intake/radionuclide | Uncertainty category[b] | Dominant cancer sites[c] |
|---|---|---|
| Inhalation[d] | | |
| $^{3}$H (HTO vapor) | A | No dominant cancer sites |
| $^{60}$Co, Type M | B | Lung >> colon |
| $^{90}$Sr, Type M | B | Lung >> red bone marrow |
| $^{106}$Ru, Type M | C | Lung >> colon |
| $^{125}$Sb, Type M | B | Lung >> colon |
| $^{131}$I, Type F | C | Thyroid |
| $^{137}$Cs, Type F | A | No dominant cancer sites |
| $^{226}$Ra, Type M | C | Lung |
| $^{232}$Th, Type S | C | Lung |
| $^{234}$U, Type M | C | Lung |
| $^{239}$Pu, Type M | C | Lung ≈ liver > bone |
| Ingestion[e] | | |
| $^{3}$H (HTO) | A | No dominant cancer sites |
| $^{60}$Co | B | Colon |
| $^{90}$Sr | A | Red bone marrow >> colon |
| $^{106}$Ru | B | Colon |
| $^{125}$Sb | B | Colon >> red bone marrow |
| $^{131}$I | C | Thyroid |
| $^{137}$Cs | A | No dominant cancer sites |
| $^{226}$Ra | C | Bone ≈ colon |
| $^{232}$Th | D | Bone ≈ colon > liver |
| $^{234}$U | C | Colon > kidney |
| $^{239}$Pu | D | Liver > colon ≈ bone |

[a] Risk coefficients for radionuclides in EPA's Federal Guidance Report No. 13 (Eckerman et al., 1999) give cancer risks per unit activity intake of radionuclides in a population of all ages.

[b] Uncertainty category for each radionuclide and route of intake obtained from Table D-1 or D-2 of Pawel et al. (2007); uncertainty categories are defined in Table 4-9. Some estimates of uncertainty differ from those given previously (Eckerman et al., 1999; Table 2.4).

[c] Sites that are the most important contributors to uncertainty in risk coefficient (Eckerman et al., 1999; Table 2.4). Contributions from uncertainties in risk models were judged to be important in all cases (Pawel et al., 2007).

[d] Type F, M, and S denote absorption types fast, medium, and slow, respectively, in model of respiratory tract currently recommended by ICRP (1994).

[e] Radionuclides are assumed to be ingested in tap water and foods.

**Table 4-11.** Summary of results of NRC-CEC expert elicitation on uncertainties in dose coefficients for intakes of radionuclides by adults calculated by ICRP[a]

| Radionuclide | Route of intake[b] | Organ or tissue | 50%/ICRP[c] | 95%/5%[d] |
|---|---|---|---|---|
| $^{131}$I | Ingestion | Thyroid | 1 | 9 |
| $^{137}$Cs | Ingestion | Colon | 1 | 4 |
| | | Red bone marrow | 1 | 4 |
| | Inhalation | Lungs | 2(F) | 50 |
| | | Red bone marrow | 1(F) | 8 |
| $^{90}$Sr | Ingestion | Colon | 1 | 600 |
| | | Red bone marrow | 0.6 | 240 |
| | | Bone surfaces | 0.5 | 390 |
| | Inhalation | Lungs | 0.7(M) | 5,300 |
| | | Red bone marrow | 1.6(M) | 35 |
| | | Bone surfaces | 1.4(M) | 28 |
| $^{144}$Ce | Inhalation | Lungs | 0.5(M) | 520[e] |
| | | Red bone marrow | 0.8(M) | 8,500 |
| | | Bone surfaces | 2(M) | 6,300[e] |
| $^{239}$Pu | Ingestion | Colon | 1 | 250 |
| | | Red bone marrow | 1 | 4,300 |
| | | Bone surfaces | 0.8 | 20,000 |
| | | Liver | 0.8 | 700[e] |
| | Inhalation | Lungs | 2(S) | 400 |
| | | Red bone marrow | 3(S) | 1,300 |
| | | Bone surfaces | 3(S) | 770 |
| | | Liver | 3(S) | 800 |

See following page for footnotes to table.

## Footnotes to Table 4-11

[a] Results of expert elicitation summarized by Goossens et al. (1998, Vol. 1; Table 4.1). Dose coefficients are 50-year committed absorbed doses per unit activity intake.

[b] Inhaled material is assumed to be respirable particles with AMAD of 1 μm.

[c] Ratio of 50$^{th}$ percentile of subjective probability distribution of dose coefficient to represent experts' combined uncertainty to dose coefficient currently recommended by ICRP. Notations F, M, and S for inhalation refer to absorption types fast, medium, and slow, respectively, in model of respiratory tract currently recommended by ICRP (1994).

[d] Ratio of 95$^{th}$ to 5$^{th}$ percentile of subjective probability distribution of dose coefficient to represent experts' combined uncertainty.

[e] Ratio is inconsistent with ratios of 95$^{th}$ to 5$^{th}$ percentiles estimated by each expert, as given in Table 4-12, and aggregated results given by Goossens et al. (1998, Vol. 2; Appendix E).

**Table 4-12.** Summary of 90% credibility intervals of dose coefficients for selected radionuclides, routes of intake, and organs or tissues in adults estimated by experts in NRC-CEC expert elicitation[a]

| Radionuclide, route of intake, and organ or tissue | Expert | 90% credibility interval of committed dose coefficient (Gy $Bq^{-1}$)[b] | | |
|---|---|---|---|---|
| | | $5^{th}$ percentile | $50^{th}$ percentile | $95^{th}$ percentile |
| $^{90}Sr$, ingestion, colon | B | $2 \times 10^{-9}$ | $1 \times 10^{-8}$ | $1 \times 10^{-7}$ |
| | C | $1.8 \times 10^{-8}$ | $5.2 \times 10^{-8}$ | $9.4 \times 10^{-8}$ |
| | D | $1 \times 10^{-8}$ | $1.5 \times 10^{-8}$ | $2.2 \times 10^{-8}$ |
| | E | $5.4 \times 10^{-9}$ | $1.8 \times 10^{-8}$ | $2.4 \times 10^{-8}$ |
| | F | $4 \times 10^{-9}$ | $1.3 \times 10^{-8}$ | $5 \times 10^{-8}$ |
| | G | $9.3 \times 10^{-11}$ | $4.4 \times 10^{-10}$ | $2.1 \times 10^{-9}$ |
| $^{90}Sr$, inhalation, lungs | B | $1 \times 10^{-10}$ | $1 \times 10^{-9}$ | $1 \times 10^{-8}$ |
| | C | $6.3 \times 10^{-8}$ | $1.9 \times 10^{-7}$ | $5.7 \times 10^{-7}$ |
| | D | $1.4 \times 10^{-7}$ | $2.1 \times 10^{-7}$ | $3.1 \times 10^{-7}$ |
| | F | $1 \times 10^{-9}$ | $1 \times 10^{-7}$ | $3 \times 10^{-7}$ |
| | G | $3.9 \times 10^{-8}$ | $2.3 \times 10^{-7}$ | $1.4 \times 10^{-6}$ |
| $^{144}Ce$, inhalation, lungs | B | $1 \times 10^{-9}$ | $3.5 \times 10^{-9}$ | $1 \times 10^{-8}$ |
| | C | $5 \times 10^{-9}$ | $3 \times 10^{-8}$ | $5 \times 10^{-8}$ |
| | D | $9.3 \times 10^{-9}$ | $2.8 \times 10^{-8}$ | $8.4 \times 10^{-8}$ |
| | F | $9 \times 10^{-10}$ | $2 \times 10^{-8}$ | $9 \times 10^{-8}$ |
| | G | $7.4 \times 10^{-8}$ | $2.2 \times 10^{-7}$ | $6.5 \times 10^{-7}$ |
| $^{144}Ce$, inhalation, red bone marrow | B | $8 \times 10^{-10}$ | $2 \times 10^{-9}$ | $6 \times 10^{-9}$ |
| | C | $3 \times 10^{-9}$ | $1.8 \times 10^{-8}$ | $3 \times 10^{-8}$ |
| | D | $1.6 \times 10^{-8}$ | $4.9 \times 10^{-8}$ | $1.5 \times 10^{-7}$ |
| | E | $1.3 \times 10^{-6}$ | $2.6 \times 10^{-6}$ | $5.2 \times 10^{-6}$ |
| | F | $4 \times 10^{-10}$ | $1 \times 10^{-8}$ | $8 \times 10^{-8}$ |
| | G | $9.4 \times 10^{-9}$ | $3.2 \times 10^{-8}$ | $1.1 \times 10^{-7}$ |
| $^{144}Ce$, inhalation, bone surfaces | B | $5 \times 10^{-8}$ | $2 \times 10^{-7}$ | $5 \times 10^{-7}$ |
| | C | $1 \times 10^{-7}$ | $1.9 \times 10^{-7}$ | $4.2 \times 10^{-7}$ |
| | D | $6.3 \times 10^{-8}$ | $1.9 \times 10^{-7}$ | $5.7 \times 10^{-7}$ |
| | E | $2.2 \times 10^{-6}$ | $4.4 \times 10^{-6}$ | $8.8 \times 10^{-6}$ |
| | F[c] | | | |

Table is continued on following page; see end of table for footnotes.

**Table 4-12.** (continued)

| Radionuclide, route of intake, and organ or tissue | Expert | 90% credibility interval of committed dose coefficient (Gy $Bq^{-1}$)[b] | | |
|---|---|---|---|---|
| | | $5^{th}$ percentile | $50^{th}$ percentile | $95^{th}$ percentile |
| $^{239}Pu$, ingestion, red bone marrow | B | $1 \times 10^{-9}$ | $8 \times 10^{-9}$ | $2 \times 10^{-7}$ |
| | C | $7.5 \times 10^{-9}$ | $3.5 \times 10^{-8}$ | $7 \times 10^{-7}$ |
| | D | $1.3 \times 10^{-9}$ | $4.0 \times 10^{-9}$ | $2.0 \times 10^{-8}$ |
| | E | $1.0 \times 10^{-12}$ | $4.5 \times 10^{-10}$ | $4.5 \times 10^{-8}$ |
| | F | $2 \times 10^{-9}$ | $2 \times 10^{-8}$ | $6 \times 10^{-8}$ |
| | G | $4 \times 10^{-8}$ | $3.9 \times 10^{-7}$ | $1.7 \times 10^{-6}$ |
| $^{239}Pu$, ingestion, bone surfaces | B | $2 \times 10^{-8}$ | $2 \times 10^{-7}$ | $3 \times 10^{-6}$ |
| | C | $5 \times 10^{-8}$ | $4.5 \times 10^{-7}$ | $9 \times 10^{-6}$ |
| | D | $2.6 \times 10^{-8}$ | $8.0 \times 10^{-8}$ | $2.4 \times 10^{-7}$ |
| | E | $9 \times 10^{-11}$ | $9 \times 10^{-9}$ | $9 \times 10^{-7}$ |
| | F | $6 \times 10^{-8}$ | $4.2 \times 10^{-7}$ | $1 \times 10^{-6}$ |
| | G | $8 \times 10^{-7}$ | $8.2 \times 10^{-6}$ | $3.1 \times 10^{-5}$ |
| $^{239}Pu$, ingestion, liver | B | $5 \times 10^{-9}$ | $4 \times 10^{-8}$ | $5 \times 10^{-7}$ |
| | C | $1.5 \times 10^{-8}$ | $7.5 \times 10^{-8}$ | $1.5 \times 10^{-6}$ |
| | D | $3.4 \times 10^{-9}$ | $1.7 \times 10^{-8}$ | $5 \times 10^{-8}$ |
| | E | $2.0 \times 10^{-11}$ | $2.0 \times 10^{-9}$ | $2.0 \times 10^{-7}$ |
| | F | $1 \times 10^{-8}$ | $8.5 \times 10^{-8}$ | $2 \times 10^{-7}$ |
| | G | $2 \times 10^{-7}$ | $1.7 \times 10^{-6}$ | $4.7 \times 10^{-6}$ |
| $^{239}Pu$, inhalation, lungs | B | $3 \times 10^{-7}$ | $3 \times 10^{-6}$ | $3 \times 10^{-5}$ |
| | C | $3 \times 10^{-6}$ | $4.5 \times 10^{-6}$ | $1 \times 10^{-5}$ |
| | D | $1.4 \times 10^{-6}$ | $4.3 \times 10^{-6}$ | $1.3 \times 10^{-5}$ |
| | F | $3 \times 10^{-6}$ | $9 \times 10^{-6}$ | $2.5 \times 10^{-5}$ |
| | G | $1.4 \times 10^{-5}$ | $6.2 \times 10^{-5}$ | $2.8 \times 10^{-4}$ |
| $^{239}Pu$, inhalation, red bone marrow | B | $1 \times 10^{-7}$ | $1 \times 10^{-6}$ | $1 \times 10^{-5}$ |
| | C | $2.5 \times 10^{-7}$ | $5 \times 10^{-7}$ | $1.5 \times 10^{-6}$ |
| | D | $1.5 \times 10^{-7}$ | $4.6 \times 10^{-7}$ | $1.4 \times 10^{-6}$ |
| | E | $1.4 \times 10^{-6}$ | $1.4 \times 10^{-5}$ | $5.6 \times 10^{-5}$ |
| | F | $8 \times 10^{-8}$ | $4.5 \times 10^{-7}$ | $2.5 \times 10^{-6}$ |
| | G | $6.8 \times 10^{-6}$ | $3.8 \times 10^{-5}$ | $2.1 \times 10^{-4}$ |

Table is continued on following page; see end of table for footnotes.

**Table 4-12.** (continued)

| Radionuclide, route of intake, and organ or tissue | Expert | 90% credibility interval of committed dose coefficient (Gy $Bq^{-1}$)[b] | | |
|---|---|---|---|---|
| | | $5^{th}$ percentile | $50^{th}$ percentile | $95^{th}$ percentile |
| $^{239}Pu$, inhalation, bone surfaces | B | $3 \times 10^{-6}$ | $3 \times 10^{-5}$ | $3 \times 10^{-4}$ |
| | C | $5 \times 10^{-6}$ | $1 \times 10^{-5}$ | $4 \times 10^{-5}$ |
| | D | $3.0 \times 10^{-6}$ | $9.0 \times 10^{-6}$ | $2.7 \times 10^{-5}$ |
| | E | $1.4 \times 10^{-4}$ | $2.7 \times 10^{-4}$ | $4.1 \times 10^{-4}$ |
| | F | $4 \times 10^{-6}$ | $9 \times 10^{-6}$ | $4 \times 10^{-5}$ |
| | G | $1.5 \times 10^{-4}$ | $7.9 \times 10^{-4}$ | $4.1 \times 10^{-3}$ |
| $^{239}Pu$, inhalation, liver | B | $1 \times 10^{-6}$ | $5 \times 10^{-6}$ | $3 \times 10^{-5}$ |
| | C | $1.5 \times 10^{-6}$ | $2.0 \times 10^{-6}$ | $8 \times 10^{-6}$ |
| | D | $6.6 \times 10^{-7}$ | $2.0 \times 10^{-6}$ | $6.0 \times 10^{-6}$ |
| | E | $3.0 \times 10^{-5}$ | $6.0 \times 10^{-5}$ | $1.2 \times 10^{-4}$ |
| | F | $5 \times 10^{-7}$ | $2 \times 10^{-6}$ | $1 \times 10^{-5}$ |
| | G | $4.0 \times 10^{-5}$ | $1.6 \times 10^{-4}$ | $6.3 \times 10^{-4}$ |

[a] Estimates obtained from Goossens et al. (1998, Vol. 2; Appendix C) for cases where uncertainty (ratio of $95^{th}$ to $5^{th}$ percentile) in Table 4-11 is factor of 400 or greater.

[b] Values are 50-year committed absorbed doses per unit activity intake; to convert to conventional units of rad $\mu Ci^{-1}$, multiply entries by $3.7 \times 10^{6}$.

[c] Expert's reported $5^{th}$ percentile of $1.2 \times 10^{-6}$ is higher than reported $95^{th}$ percentile of $7 \times 10^{-7}$ (Goossens et al., 1998, Vol. 2; Appendix C), and correct values cannot be determined.

**Table 4-13.** Estimates by ICRP task group of uncertainty in GI-tract absorption fraction ($f_1$) for radionuclides in adults and effect of uncertainty in $f_1$ on uncertainty in committed effective dose from ingestion calculated by ICRP[a]

| Radionuclide | Half-life | Uncertainty in $f_1$[b] | Effect on uncertainty in committed effective dose[b] |
|---|---|---|---|
| $^{3}H$ | 12.33 y | 1.1 | 1.0 |
| $^{60}Co$ | 5.27 y | 10 | 2.6 |
| $^{90}Sr$ | 28.8 y | 4 | 3.5 |
| $^{95}Zr$ | 64 d | 100 | 1.1 |
| $^{106}Ru$ | 1.02 y | 20 | 1.4 |
| $^{125}Sb$ | 2.76 y | 100 | 2.4 |
| $^{131}I$ | 8.02 d | 1.1 | 1.1 |
| $^{137}Cs$ | 30.1 y | 1.3 | 1.2 |
| $^{210}Pb$ | 22.3 y | 6 | 6.4 |
| $^{226}Ra$ | 1600 y | 6 | 5.5 |
| $^{238}U$ | $4.47 \times 10^{9}$ y | 5 | 4.1 |
| $^{239}Pu$ | $2.41 \times 10^{4}$ y | 10[c] | 9.3 |

[a] Estimates of uncertainty obtained from Harrison et al. (2001; Tables 1 and 2).

[b] Ratio of 95$^{th}$ to 5$^{th}$ percentiles of subjective probability distribution.

[c] Data in animals discussed by Harrison et al. (2001) suggest that uncertainty in $f_1$ for plutonium in oxide form could be much greater than factor of 10.

**Table 4-14.** Summary of assumed uncertainties in estimated dose coefficients for inhalation of radionuclides in resuspended fallout at NTS[a]

| Source of uncertainty[b] | Probability distribution |
|---|---|
| Fission and Activation Products | |
| Dosimetric and biokinetic models recommended by ICRP | Lognormal distribution with median at 1.0 and 90% credibility interval between 0.1 and 10 |
| Bias in dose coefficients recommended by ICRP (inhalation of nonrespirable particles)[c] | Uniform distribution between 0.25 and 1.0 |
| Plutonium[d] | |
| Dosimetric and biokinetic models recommended by ICRP | Lognormal distribution with median at 1.0 and 90% credibility interval between 0.033 and 30 |
| Bias in dose coefficients recommended by ICRP (inhalation of nonrespirable particles)[c] | Log-uniform distribution between ($ln$ 0.1) = −2.3 and ($ln$ 1.0) = 0[e] |

[a] Analysis of uncertainties in dose coefficients is described in Section 4.1.5. Resulting uncertainties in dose coefficients for inhalation of fission and activation products or plutonium in respirable or nonrespirable form are summarized in Section 4.1.5.5 and Table 4-15.

[b] All uncertainties are relative to dose coefficients for inhalation of radionuclides in respirable or nonrespirable oxide form by adult members of the public currently recommended by ICRP [(1996a; 2002) and references therein].

[c] Bias represents assumed tendency of dose coefficients currently recommended by ICRP to overestimate doses from inhalation of larger, nonrespirable fallout particles. ICRP's dose coefficients for inhalation of smaller, respirable particles are assumed to be unbiased.

[d] Uncertainty in biological effectiveness of alpha particles relative to photons and electrons is not taken into account (see Section 4.1.5.4.2).

[e] Lower and upper bound of bias in ICRP's dose coefficients is assumed to be 0.1 and 1.0, respectively.

**Table 4-15.** Summary of assumed uncertainties in parameters to estimate dose from inhalation of radionuclides in fallout resuspended by nuclear detonations at NTS[a]

| Parameter[b] | Radionuclides and particle size[c] | Median value (90% credibility interval) |
|---|---|---|
| Concentrations of radionuclides on ground surface[d] | Fission/activation products | |
| | Respirable particles | 1.2 (0.32, 4.4) |
| | Nonrespirable particles | 0.93 (0.19, 3.5) |
| | Plutonium | 2.2 (0.60, 7.7) |
| Resuspension factor ($m^{-1}$) | All radionuclides | |
| | Respirable particles, thermal-pulse region | $1 \times 10^{-6}$ ($4 \times 10^{-8}$, $5 \times 10^{-5}$) |
| | Nonrespirable particles, thermal-pulse region | $8 \times 10^{-6}$ ($3 \times 10^{-7}$, $2 \times 10^{-4}$) |
| | Respirable particles, blast-wave region | $1 \times 10^{-8}$ ($7 \times 10^{-11}$, $3 \times 10^{-6}$) |
| | Nonrespirable particles, blast-wave region | $8 \times 10^{-8}$ ($4 \times 10^{-10}$, $1 \times 10^{-5}$) |
| Breathing rate ($m^3\ h^{-1}$) | | 1.1 (0.6, 2.0) |
| Dose coefficients[e] | Fission/activation products | |
| | Respirable particles | 1.0 (0.1, 10) |
| | Nonrespirable particles | 0.6 (0.054, 6.4) |
| | Plutonium | |
| | Respirable particles | 1.0 (0.033, 30) |
| | Nonrespirable particles | 0.3 (0.0087, 12) |

[a] Model to estimate dose from inhalation of resuspended radionuclides is given in eq. (5) (see Section 3.1), and uncertainties in model parameters are described in Sections 4.1.1−4.1.5.

[b] Uncertainties in parameters that contribute to estimated uncertainties in concentrations of radionuclides in fallout deposited on ground surface, resuspension factors, and dose coefficients for inhalation are summarized in Tables 4-1, 4-7, and 4-14, respectively.

[c] If particle size is not indicated, uncertainty applies to respirable and nonrespirable particles.

[d] Probability distributions to represent uncertainties are relative to point estimates that are assumed in dose reconstructions for military participants.

[e] Probability distributions to represent uncertainties are relative to dose coefficients for inhalation of radionuclides in respirable or nonrespirable oxide form by adult members of the public currently recommended by ICRP [(1996a; 2002) and references therein]. Uncertainty in biological effectiveness of alpha particles relative to photons and electrons is not taken into account (see Section 4.1.5.4.2).

**Table 4-16.** Summary of results of analysis of uncertainties in estimated organ-specific equivalent doses from inhalation of mixtures of fission and activation products in fallout resuspended by nuclear detonations at NTS[a]

| Region[b] | Particle size[c] | Probability distribution of inhalation dose | | |
|---|---|---|---|---|
| | | 5th percentile | 50th percentile | 95th percentile |
| Thermal-pulse | Respirable | $2 \times 10^{-8}$ | $2 \times 10^{-6}$ | $2 \times 10^{-4}$ |
| | Nonrespirable | $5 \times 10^{-8}$ | $4 \times 10^{-6}$ | $3 \times 10^{-4}$ |
| Blast-wave | Respirable | $5 \times 10^{-11}$ | $2 \times 10^{-8}$ | $8 \times 10^{-6}$ |
| | Nonrespirable | $1 \times 10^{-10}$ | $3 \times 10^{-8}$ | $1 \times 10^{-5}$ |

[a] Estimated doses are relative to activity concentrations of fission and activation products in fallout deposited on ground surface at NTS that are assumed in dose reconstructions for military participants and relative to dose coefficients for specific organs or tissues from inhalation of fission and activation products in respirable or nonrespirable oxide form by adult members of the public that are currently recommended by ICRP [(1996a; 2002) and references therein]; doses are in units of $m^2\ h^{-1}$ and give equivalent dose (rem $h^{-1}$) per unit concentration on ground surface (Ci $m^{-2}$) and per unit equivalent dose per activity intake (rem $Ci^{-1}$). Comparable quantity calculated in dose reconstructions is product of assumed resuspension factor and breathing rate.

[b] Thermal-pulse region is region closest to ground zero where initial pulse of thermal radiation produced in nuclear detonations was important in causing resuspension; blast-wave region is region beyond thermal-pulse region where resuspension was caused by blast wave (see Section 2).

[c] Respirable particles are assumed to have diameter of 10 μm or less, and nonrespirable particles are assumed to have diameter up to 100 μm. When inhalation of nonrespirable particles is assumed, doses can be estimated using dose coefficients for ingestion that are adjusted to account for the fraction of inhaled material that is swallowed.

**Table 4-17.** Summary of results of analysis of uncertainties in estimated organ-specific equivalent doses from inhalation of plutonium in fallout resuspended by nuclear detonations at NTS[a]

| Region[b] | Particle size[c] | Probability distribution of inhalation dose | | |
|---|---|---|---|---|
| | | 5th percentile | 50th percentile | 95th percentile |
| Thermal-pulse | Respirable | $2 \times 10^{-8}$ | $3 \times 10^{-6}$ | $6 \times 10^{-4}$ |
| | Nonrespirable | $4 \times 10^{-8}$ | $6 \times 10^{-6}$ | $1 \times 10^{-3}$ |
| Blast-wave | Respirable | $5 \times 10^{-11}$ | $3 \times 10^{-8}$ | $2 \times 10^{-5}$ |
| | Nonrespirable | $8 \times 10^{-11}$ | $5 \times 10^{-8}$ | $3 \times 10^{-5}$ |

[a] Estimated doses are relative to activity concentrations of plutonium in fallout deposited on ground surface at NTS that are assumed in dose reconstructions for military participants and relative to dose coefficients for specific organs or tissues from inhalation of plutonium in respirable or nonrespirable oxide form by adult members of the public that are currently recommended by ICRP [(1996a; 2002) and references therein]; doses are in units of $m^2\ h^{-1}$ and give equivalent dose (rem $h^{-1}$) per unit concentration on ground surface (Ci $m^{-2}$) and per unit equivalent dose per activity intake (rem $Ci^{-1}$). Comparable quantity calculated in dose reconstructions is product of assumed resuspension factor and breathing rate.

[b] Thermal-pulse region is region closest to ground zero where initial pulse of thermal radiation produced in nuclear detonations was important in causing resuspension; blast-wave region is region beyond thermal-pulse region where resuspension was caused by blast wave (see Section 2).

[c] Respirable particles are assumed to have diameter of 10 μm or less, and nonrespirable particles are assumed to have diameter up to 100 μm. When inhalation of nonrespirable particles is assumed, doses can be estimated using dose coefficients for ingestion that are adjusted to account for the fraction of inhaled material that is swallowed.

## 5. DERIVATION OF EFFECTIVE RESUSPENSION FACTORS

The purpose of the analysis in Section 4 is to develop probability distributions to represent uncertainties in estimates of doses from inhalation of radionuclides in fallout that was resuspended in the thermal-pulse or blast-wave region of nuclear detonations at NTS. By comparing upper 95% credibility limits ($95^{th}$ percentiles) of probability distributions of uncertain inhalation doses with point estimates that would be obtained on the basis of the model that is used to estimate inhalation doses to military participants in other scenarios that involved resuspension of radionuclides, effective resuspension factors that should be assumed in estimating inhalation doses in the thermal-pulse and blast-wave regions can be derived.

In the analysis in Section 4, uncertainties in the concentrations of fission and activation products or plutonium in fallout that was deposited on the ground surface and uncertainties in dose coefficients for inhalation of radionuclides in respirable or nonrespirable form are estimated relative to point values normally assumed in dose reconstructions. Therefore, to derive effective resuspension factors that should be assumed in dose reconstructions on the basis of the model in eq. (5) (see Section 3.1), upper 95% credibility limits of inhalation doses obtained in our analysis are equated to $1.2 \times K_{eff}$, where 1.2 is the usual breathing rate in $m^3\ h^{-1}$ (Egbert et al., 1985; Raine et al., 2007) and $K_{eff}$ is the effective resuspension factor in $m^{-1}$. This approach takes into account that dose reconstructions in other resuspension scenarios incorporate an assumption that all resuspended radionuclides were inhalable.

To obtain effective resuspension factors that would be sufficiently high to ensure that estimated inhalation doses in resuspension scenarios of concern would be at least upper 95% credibility limits in all cases, the combination of radionuclides (fission and activation products or plutonium) and particle size (respirable or nonrespirable) that results in the highest upper 95% credibility limit of an estimated inhalation dose should be used (see Section 4.2.4). Since results of our analysis in Tables 4-16 and 4-17 indicate that the limiting case is inhalation of plutonium in nonrespirable form, effective resuspension factors in the thermal-pulse and blast-wave regions, which are calculated to one significant figure, are estimated as follows:

Thermal-Pulse Region

$$(1.2\ m^3\ h^{-1}) \times K_{eff}\ (m^{-1}) = 1 \times 10^{-3}\ m^2\ h^{-1},$$

$$K_{eff} = 8 \times 10^{-4}\ m^{-1}\ .$$

Blast-Wave Region

$$(1.2\ m^3\ h^{-1}) \times K_{eff}\ (m^{-1}) = 3 \times 10^{-5}\ m^2\ h^{-1},$$

$$K_{eff} = 3 \times 10^{-5}\ m^{-1}\ .$$

In dose reconstructions for other resuspension scenarios, assumed resuspension factors are given to the nearest power of 10 (Barrett et al., 1986; Phillips et al., 1985) to reflect their large uncertainties. By using the same approach in the high-resuspension scenarios of concern to this report and rounding up, we obtain the following effective resuspension factors that should be assumed in dose reconstructions:

- Resuspension in thermal-pulse region – $K_{eff} = 10^{-3}\ m^{-1}$;
- Resuspension in blast-wave region – $K_{eff} = 10^{-4}\ m^{-1}$.

Again, these are resuspension factors that should be applied to all radionuclides on the ground surface in dose reconstructions for scenarios that involved resuspension of previously deposited fallout by nuclear detonations at NTS to ensure that inhalation doses that are estimated using point values of other parameters normally assumed in dose reconstructions (i.e., concentrations of radionuclides on the ground surface, the breathing rate, and dose coefficients for inhalation) would be at least upper 95% credibility limits.

We note that effective resuspension factors of $10^{-3}$ and $10^{-4}\ m^{-1}$ also would be obtained if inhalation of respirable, rather than nonrespirable, particles were assumed to be the limiting case. This assumption could apply, for example, if exposure in the thermal-pulse or blast-wave region did not occur until a sufficiently long time after detonation that larger, nonrespirable fallout particles would have fallen to Earth and only smaller, respirable particles remained airborne. In such cases, results in Table 4-17 indicate that effective resuspension factors calculated as above would be reduced by about one-third compared with values obtained by assuming inhalation of

nonrespirable particles. However, when calculated effective resuspension factors are rounded up to the nearest power of 10, the same values that should be assumed in dose reconstructions, as derived above, are obtained.

Current policy and procedures of the NTPR Program specify that upper bounds of inhalation doses should be calculated by applying an uncertainty factor of 10 to point estimates that are obtained in dose reconstructions (DTRA, 2007; Case et al., 2008). However, this uncertainty factor should not be applied in estimating inhalation doses in the high-resuspension scenarios in which effective resuspension factors derived in this report should be assumed. Effective resuspension factors were selected to ensure that at least upper 95% credibility limits of inhalation doses in the thermal-pulse and blast-wave regions would be obtained for all radionuclides and organs or tissues. Therefore, no additional adjustment of doses is needed when they are calculated using these resuspension factors and point values of the concentrations of radionuclides on the ground surface, the breathing rate, and dose coefficients for inhalation normally used in dose reconstructions.[59]

The derivation of effective resuspension factors in the thermal-pulse and blast-wave regions presented in this report is based on an assumption that current methods of dose reconstruction for scenarios that involved inhalation of resuspended radionuclides will continue to be used. That is, we have assumed that inhalation doses in the high-resuspension scenarios of concern to this report will be calculated using point estimates of all parameters in the model in eq. (5), and that credible upper bounds (at least upper 95% credibility limits) will be obtained by using effective resuspension factors derived in this report.

[59] Regulations on methods of estimating dose in 32 CFR Part 218 and policies and standard operating procedures of the NTPR Program (DTRA, 2007; Case et al., 2008) specify that central estimates (e.g., mean values) of external or internal doses to participants, as well as upper bounds (at least upper 95% credibility limits), should be calculated and reported in all cases. In the high-resuspension scenarios of concern to this report, the appropriate central estimate of an inhalation dose is the median. Results in Tables 4-16 and 4-17 indicate that the median dose in the thermal-pulse region is about two orders of magnitude less than the upper bound that is calculated using an effective resuspension factor, and that the median dose in the blast-wave region is between two and three orders of magnitude less than the upper bound. The ratio of the upper bound to the median dose is higher for plutonium than for mixtures of fission and activation products. Use of the mean dose to represent a central estimate is inappropriate in these scenarios, because the mean dose is close to or greater than the upper 95% credibility limit when the uncertainty is as large as indicated in Tables 4-16 and 4-17.

However, if methods of dose reconstruction for all resuspension scenarios were changed to incorporate an explicit accounting of uncertainties in all model parameters (i.e., if fully probabilistic methods of dose reconstruction were used), effective resuspension factors derived in this report would no longer need to be used in calculating credible upper bounds of inhalation doses due to resuspension of previously deposited fallout in the thermal-pulse or blast-wave regions of nuclear detonations at NTS. Rather, the analyses in this report could provide a basis for assumed probability distributions to represent uncertainties in all parameters in the model in eq. (5), including resuspension factors that apply to inhalable radionuclides in respirable or nonrespirable form. Results of a fully probabilistic uncertainty analysis then could be used to select a credible upper bound ($95^{th}$ percentile) of inhalation dose in a given scenario. Methods of probabilistic uncertainty analysis are being developed for use in dose reconstructions for military participants in the NTPR Program (Case et al., 2009).

# 6. DISCUSSION OF RESULTS

This report has presented an assessment of uncertainties in estimates of inhalation dose due to resuspension of previously deposited fallout by nuclear detonations at NTS using estimates of relevant parameters and their uncertainties that are intended to be reasonably realistic. Result of this uncertainty analysis were used to derive point values of effective resuspension factors in the thermal-pulse and blast-wave regions of nuclear detonations that should be assumed in dose reconstructions to ensure that estimated inhalation doses to military participants in the resuspension scenarios of concern are at least upper 95% credibility limits.

The following sections discuss (1) the importance of judgment in deriving effective resuspension factors and the credibility of the results and (2) the applicability of the results, including the extent of the thermal-pulse and blast-wave regions and the time periods after a detonation when effective resuspension factors should be applied in those regions.

## 6.1 Importance of Judgment and Credibility of Results

Discussions in Section 4 have emphasized that the development of probability distributions to represent uncertainty in many parameters that are used to estimate inhalation doses in the resuspension scenarios of concern to this report is highly judgmental, due to a paucity of relevant data. Probability distributions that were developed in this report to represent uncertainty in the resuspension factors that apply to all previously deposited fallout in the thermal-pulse and blast-wave regions, the inhalable fraction of radionuclides in resuspended fallout, the respirable fraction of inhalable radionuclides, dose coefficients recommended by ICRP, and bias factors to represent the tendency of ICRP's dose coefficients to overestimate doses from inhalation of radionuclides in nonrespirable form all were based to a significant extent on subjective scientific judgment. The only parameter that can be estimated with small uncertainty on the basis of relevant data is the breathing rate. However, uncertainties in some parameters cannot be large even though they must be estimated on the basis of judgment. For example, although the degree of fractionation of radionuclides in fallout from particular

detonations is poorly known, the effects of fractionation on estimated inhalation doses can be bounded with relatively small uncertainty on the basis of knowledge of the boiling points of chemical elements in weapons debris and the yields of each mass chain in the different fission modes of concern (Trabalka and Kocher, 2007).

Although subjective scientific judgment was used extensively in our analysis, we believe that use of the effective resuspension factors derived in this report should provide credible upper bounds (at least upper 95% credibility limits) of inhalation doses in the high-resuspension scenarios of concern. Since resuspension factors that are assumed in dose reconstructions are given to the nearest power of 10, to reflect their large uncertainties, an increase in the derived effective resuspension factors by an order of magnitude (i.e., from $10^{-3}$ to $10^{-2}$ $m^{-1}$ in the thermal-pulse region and from $10^{-4}$ to $10^{-3}$ $m^{-1}$ in the blast-wave region) should not be required to ensure that credible upper bounds of inhalation doses are obtained. This conclusion is based on several considerations, which are summarized below.

- Although data on resuspension factors that apply to all previously deposited fallout that could be resuspended by nuclear detonations at NTS are lacking, the assumed upper credibility limits of $10^{-2}$ $m^{-1}$ and $10^{-3}$ $m^{-1}$ in the thermal-pulse and blast-wave regions, respectively, must be close to the maximum possible values, because they represent an assumption that nearly all fallout was resuspended by a detonation when estimates of the height of the cloud of resuspended material in the two regions, as inferred from photographs at several detonations, are taken into account.
- Although the uncertainty of a factor of 3 that is assumed to apply to estimates of photon exposure rates at any location at a fixed time after each detonation is based mainly on judgment, we believe it is highly unlikely that this uncertainty could be substantially higher (e.g., a factor of 10 or more), especially at locations of higher concentrations of fallout and, thus, higher estimates of dose from inhalation of resuspended fallout. Patterns of fallout at NTS that are inferred from dose-rate contours at 1 hour after detonation (Hawthorne, 1979) do not appear to be highly irregular—i.e., there is little evidence of localized areas of much higher or lower concentrations than in proximate

areas. The apparent regularity of patterns of fallout provides confidence in the validity of interpolations or extrapolations of measurements at a limited number of locations. The uncertainty in estimated photon exposure rates that are based on measurement would need to be much greater than a factor of 3 to affect effective resuspension factors that were derived in this report. However, it seems highly unlikely that this uncertainty could be comparable to the most important uncertainties, including uncertainties in resuspension factors that apply to all fallout on the ground surface, the inhalable fraction of resuspended radionuclides, and dose coefficients for inhalation.

- On the basis of available data on particle-size distributions of activity in fallout from tower shots at NTS, which produced most of the fallout of concern to this report, and the consideration that airborne concentrations of dust that can be tolerated while breathing are much lower than concentrations that would be calculated on the basis of the assumed upper credibility limits of resuspension factors that apply to all material on the ground surface, only a small fraction of resuspended radionuclides could have remained in the air to be inhaled by participants who were located in the blast-wave region at the time of a detonation or who entered the blast-wave or thermal-pulse region shortly thereafter. Inhalable fractions of resuspended radionuclides could have been large only if most large particles that were dominant in fallout at NTS were transformed into smaller particles prior to or during resuspension but there was no such effect on larger soil particles. Such a pronounced difference in particle-size distributions of resuspended fallout and native soil does not seem plausible.
- Available data on particle-size distributions of activity in fallout also suggest that our assumed $95^{th}$ percentiles of the inhalable fraction of resuspended radionuclides (0.1) and the respirable fraction of resuspended radionuclides in inhalable form (0.59) are higher than would be needed to provide at least upper 95% credibility limits of possible values in areas where concentrations of fallout and, thus, potential inhalation doses were relatively high.
- Our assumption that, on average, about 20% of all resuspended radionuclides in inhalable form were respirable should not be a substantial underestimate when (1) the range of

diameters of respirable particles (0–10 μm) is slightly more than 20% of the assumed range of diameters of inhalable particles (0–44 μm) and (2) it is unlikely that respirable particles contained most of the activity in inhalable particles.

- Although information on uncertainties in dose coefficients for inhalation and ingestion of radionuclides that are currently recommended by ICRP is limited, especially in regard to dose coefficients for organs or tissues at minor sites of deposition, the assumed uncertainties would need to greatly underestimate possible differences between ICRP's dose coefficients and values that apply to individual participants to affect the derived effective resuspension factors. If assumed uncertainties in other parameters are unchanged, an increase in the effective resuspension factors by an order of magnitude would be obtained only if the upper 95% credibility limit of a dose coefficient were nearly a factor of 100 greater than ICRP's dose coefficient. Such a large uncertainty seems unreasonable, even at minor sites of deposition, when deposition fractions at major sites have small uncertainties and only a small fraction of radionuclides that are absorbed into blood is deposited at minor sites.
- Even if it were assumed that there is no bias in ICRP's dose coefficients for inhalation of radionuclides in nonrespirable form, which seems unlikely when refractory radionuclides (e.g., plutonium) should tend to be dispersed in the volume of larger, insoluble fallout particles, the effect on our results would be small. By assuming no bias, the limiting effective resuspension factor in the thermal-pulse region that would be obtained in our analysis would increase to slightly above $10^{-3}$ $m^{-1}$, and $10^{-3}$ $m^{-1}$ would still be the appropriate value to the nearest power of 10 for use in dose reconstructions.

An additional consideration is that inhalation doses to organs or tissues at minor sites of deposition of radionuclides should be unimportant even when high resuspension factors in the thermal-pulse and blast-wave regions and unusually high concentrations of radionuclides in previously deposited fallout at NTS are assumed (NCRP, 2003; Appendix E). Doses from inhalation of resuspended fallout in the thermal-pulse or blast-wave region that would be significant relative to minimum doses that are required to qualify a claimant for compensation

for cancer (Kocher and Apostoaei, 2007) are possible only in organs or tissues at major sites of deposition (e.g., lung, bone, red bone marrow, liver), and uncertainties in dose coefficients in those organs or tissues should be substantially lower than uncertainties assumed in our analysis.

Furthermore, when doses from inhalation of long-lived radionuclides with long retention times in the body (e.g., plutonium), which deliver doses at essentially a constant rate, are important, use of 50-year committed doses per unit activity intake that are assigned to the year of intake could result in overestimates of the dose that could have caused a participant's cancer. However, this potential source of bias in estimated doses becomes less important as the time since exposure when a cancer is diagnosed increases. Indeed, use of 50-year committed doses could result in underestimates of the dose that could have caused a participant's cancer as the time since exposure when cancer is diagnosed increases beyond 50 years.[60]

It may seem that the effective resuspension factors of $10^{-3}$ $m^{-1}$ in the thermal-pulse region and $10^{-4}$ $m^{-1}$ in the blast-wave region that were derived in this report are too low when they are compared with resuspension factors that are assumed in dose reconstructions for other resuspension scenarios. For example, a resuspension factor of $10^{-5}$ $m^{-1}$ is often assumed in scenarios that involved walking, marching, trucking, or busing through a fallout field or touring of display areas, and resuspension factors as high as $10^{-3}$ or $10^{-2}$ $m^{-1}$ have been assumed in scenarios that involved helicopter landings and takeoffs or assaults or marches behind armored vehicles [Barrett et al. (1986; Table 5); NCRP (2003; Table IV.C.2)], and it is reasonable to suppose that resuspension factors in the thermal-pulse and blast wave regions are substantially higher than resuspension factors that should be assumed in some of those scenarios, especially scenarios that involved resuspension by walking or light vehicular activity.

It is important to recognize, however, that assumed resuspension factors in other scenarios are intended to substantially exceed expected values (Barrett et al., 1986), and that

[60] The times since exposure when use of 50-year committed doses that are assigned to the year of intake could result in underestimates of the dose that could have caused a participant's cancer depend on the minimum latency period for the cancer type of concern, which is about 5−10 years for most solid cancers, 4–6 years for thyroid and bone cancer, and 2−3 years for leukemias (Land et al., 2003; Kocher et al., 2008). Thus, for example, doses that could have caused most solid cancers could be underestimated when a cancer is diagnosed more than about 55–60 years after intakes of long-lived radionuclides with long retention times in the body.

dose reconstructions for those scenarios do not consider the possibility that only a fraction of the resuspended radioactive material was inhalable or respirable. An accounting of the inhalable and respirable fractions could be important to obtaining realistic estimates of inhalation dose in scenarios that involved resuspension by vigorous disturbances of surface soil (e.g., helicopter landings and takeoffs, assaults or marches behind armored vehicles). Furthermore, the assumptions of a resuspension factor of $10^{-3}$ $m^{-1}$ in the thermal-pulse region and a height of the cloud of resuspended material in that region of about 100 m (see Section 4.1.3.1.1) are equivalent to assuming that about 10% of all fallout on the ground surface was resuspended, so a much higher effective resuspension factor that takes into account the inhalable and respirable fractions of resuspended fallout would not be reasonable. Similar considerations apply in the blast-wave region, where the height of the cloud of resuspended material was substantially lower than in the thermal-pulse region.

On the basis of these considerations, we believe that the analysis presented in this report provides effective resuspension factors in the thermal-pulse and blast-wave regions of nuclear detonations at NTS that would result in estimates of inhalation dose that are credible upper bounds (at least upper 95% credibility limits). Thus, the derived effective resuspension factors should give participants the benefit of the doubt in estimating inhalation doses, as required by a policy of the NTPR Program (DTRA, 2007).

We also believe that it would not be reasonable to reduce the effective resuspension factors that were derived in this report by an order of magnitude and still ensure that estimated inhalation doses would be credible upper bounds. Consider, for example, resuspension in the blast-wave region. An analysis in Section V.C.3.3 of the NRC (2003) report, in which uncertainties in many parameters in the model in eq. (5) (see Section 3.1) were considered, suggests that a resuspension factor of $10^{-5}$ $m^{-1}$ is required to obtain credible upper bounds of inhalation doses in scenarios that involved resuspension by walking or light vehicular traffic; this is the resuspension factor that is normally assumed in dose reconstructions for these scenarios (Barrett et al., 1986; Table 5). Given that the high winds of about 100–200 mph near the inner boundary of the blast-wave region (see Section 2.2 and Table 2-1) should be more effective in causing resuspension than walking or light vehicular traffic, an assumption that an effective

resuspension factor of $10^{-5}$ $m^{-1}$ in the blast-wave region would provide credible upper bounds of inhalation dose does not seem plausible. Effective resuspension factors that are an order of magnitude lower than the values we derived could be obtained only if unreasonably low uncertainties in important parameters were assumed.

## 6.2 Applicability of Effective Resuspension Factors

Effective resuspension factors derived in this report are intended to be applied in regions near ground zero of nuclear detonations at NTS and for time periods after detonation when resuspended radionuclides remained airborne and could have been inhaled by participants. The following sections consider how the extent of the thermal-pulse and blast-wave regions and the time periods for applying the effective resuspension factors in those regions might be defined.

### 6.2.1 *Extent of Thermal-Pulse and Blast-Wave Regions*

The extent of the thermal-pulse and blast-wave regions is discussed in Section 2. On the basis of a statement by Glasstone and Dolan (1977), dose reconstructions should assume that the thermal-pulse region extended to a distance from ground zero where the peak overpressure associated with the blast wave was 6 psi. This distance, which should be no more than about 1.4 miles, can be estimated at any shot using Figure 2-2 and scaling of the burst height and distance from ground zero by the cube root of the yield in kt (see Section 2.1).

The extent of the blast-wave region is difficult to define when the maximum wind speed that was associated with a blast wave decreased with distance from ground zero and the wind speed that caused unusually high resuspension when the wind persisted for a short time (no more than a few seconds) is largely unknown. Section 2.2 discussed an assumption that the blast-wave region extended to a distance where the maximum wind speed was about 40–70 mph and the corresponding peak overpressure was about 1–2 psi. On the basis of the following argument, we believe it is reasonable to assume that the blast-wave region extended to a distance where the

peak overpressure was 2 psi in the absence of information on the extent of the dust cloud at specific shots, and that resuspension by the blast wave was not important at greater distances.

The effective resuspension factor of $10^{-4}$ $m^{-1}$ in the blast-wave region that was derived in Section 5 is intended to be an average value that applies to the range of maximum wind speeds that caused significant resuspension in that region. On the basis of the conclusion that an effective resuspension factor of $10^{-3}$ $m^{-1}$ should be assumed in the thermal-pulse region to obtain credible upper bounds of inhalation doses and the consideration that resuspension in the inner portion of the blast-wave region, where the maximum wind speed was the highest, was substantially less than in the thermal-pulse region, as indicated by the photograph in Figure 2-1 and discussed in Section 4.1.3.1.2, we believe that an effective resuspension factor of $10^{-5}$ $m^{-1}$ would be sufficient to provide credible upper bounds of inhalation doses at the greatest distances from ground zero where the blast wave was a significant cause of resuspension. As noted in Section 6.1, a resuspension factor of $10^{-5}$ $m^{-1}$ normally is assumed in estimating inhalation doses in scenarios that involved resuspension by walking, marching, trucking, or busing through a fallout field or touring of display areas. Therefore, by assuming that an effective resuspension factor of $10^{-4}$ $m^{-1}$ would not need to be applied beyond the 2-psi line, a resuspension factor of $10^{-5}$ $m^{-1}$ would be assumed at all locations beyond that line where exposure to previously deposited fallout could have occurred. In effect, at distances beyond the 2-psi line, resuspension by the blast wave is assumed to be indistinguishable from resuspension due to activities of participants. As a consequence of the assumed extent of the blast-wave region, there is assumed to be a transition from an effective resuspension factor of $10^{-3}$ $m^{-1}$ in the thermal-pulse region, where resuspension was the highest, to a value of $10^{-4}$ $m^{-1}$ between the outer boundary of the thermal-pulse region and the distance where the peak overpressure associated with the blast wave was 2 psi, to a value of $10^{-5}$ $m^{-1}$ beyond the 2-psi line where activities of participants, rather than the blast wave, are assumed to be the most important cause of resuspension.

If the maximum extent of the blast-wave region is assumed to be defined by the 2-psi line, this region probably extended to a distance from ground zero of about 2.5 miles or less (see Section 2.2). However, given the difficulty in defining the maximum extent, we believe that any

reports of unusually high dust loadings at times shortly after a detonation should be taken into account in defining the extent of the blast-wave region at specific detonations.

### **6.2.2** *Time Periods for Applying Effective Resuspension Factors*

The time period after a detonation during which the effective resuspension factors in the thermal-pulse and blast-wave regions that were derived in this report should be applied generally depends on the particle size of resuspended material and the maximum height of the cloud of resuspended fallout. The appropriate time period also could depend on the speed and direction of the winds close to the ground surface at times after a detonation when participants were located in or near the thermal-pulse or blast-wave region, because surface winds would tend to disperse resuspended material. In the following discussion, however, the effect of surface winds, which often were very low at times of detonations at NTS (Hawthorne, 1979), is ignored.

In the thermal-pulse region, we estimated that the maximum height of a cloud of resuspended fallout might be about 100 m or more (see Section 4.1.3.1.1). In Section 5, we showed that an effective resuspension factor of $10^{-3}$ $m^{-1}$ should be assumed in this region even if only respirable particles of diameter 10 μm or less remained airborne at times of exposure. If an average diameter of respirable particles of 5 μm is assumed, the average settling velocity of a fallout particle of density 2.7 g $cm^{-3}$, as calculated using Stokes Law and assuming a dynamic shape factor of 1.3, would be about 0.16 cm $s^{-1}$ (Hinds, 1982). Therefore, on average, the time required for redeposition of resuspended fallout particles in respirable form from a height of 100 m would be about 17 hours. The afterwind noted in Section 1, which was caused by the rising fireball, presumably increased the time period over which some resuspended fallout in the thermal-pulse region remained airborne. Given that the height of a cloud of resuspended fallout in the thermal-pulse region may have been greater than 100 m, fall times of respirable particles from the top of the cloud may have been longer than 17 hours; the fall time would increase in proportion to an increase in cloud height. Therefore, to ensure that credible upper bounds of inhalation doses would be obtained, we believe it is reasonable to assume that an effective resuspension factor of $10^{-3}$ $m^{-1}$ should be used to estimate inhalation doses to participants who

entered the thermal-pulse region within a day after a detonation. Again, this recommendation assumes that winds were not important in dispersing resuspended radionuclides over that period.

As indicated in Figure 2-1, the height of a cloud of resuspended fallout in the blast-wave region was substantially less than in the thermal-pulse region. Therefore, the time period during which resuspended fallout in respirable form remained airborne in the blast-wave region also was substantially less.

On the basis of Figure 2-1 and other photographs of nuclear detonations (AFLML, 1951), it appears that that the height of the cloud of resuspended fallout in the blast-wave region was no more than a few tens of meters (see Section 4.1.3.1.2). If a maximum height of 30 m is assumed, we estimate that respirable fallout particles with an assumed average diameter 5 μm and average settling velocity of 0.16 cm $s^{-1}$, as estimated above, remained airborne for about 5 hours at most. Since the height of the cloud in most of the blast-wave region presumably was less than 30 m and the concentrations of resuspended radionuclides presumably were less at the top of a cloud in this region than near the ground surface, an assumption that exposure to resuspended fallout could have occurred up to 5 hours after a detonation should represent a reasonable bounding condition. We believe that this assumption is appropriate to ensure that estimated inhalation doses in the blast-wave region are credible upper bounds if winds were not important in dispersing resuspended radionuclides over that period. We also reiterate that a resuspension factor of $10^{-5}$ $m^{-1}$ would be applied in the blast-wave region at times beyond 5 hours to account for resuspension by such participant activities as marching, trucking, or busing (Barrett et al., 1986; Table 5).

# 7. SUMMARY OF RESULTS

This report has presented an analysis to derive effective resuspension factors that should be assumed in exposure scenarios that involved resuspension of previously deposited fallout by nuclear detonations at NTS to ensure that point estimates of inhalation dose that are obtained in dose reconstructions for military participants would be credible upper bounds (at least upper 95% credibility limits). Effective resuspension factors that should be applied in two regions near ground zero of a detonation were derived: the thermal-pulse region closest to ground zero, where the initial thermal pulse was important in causing resuspension, and the blast-wave region farther from ground zero, where resuspension was caused only by the blast wave. The results of this analysis are summarized as follows:

Thermal-Pulse Region

- An effective resuspension factor of $10^{-3}$ $m^{-1}$ should be assumed;
- The thermal-pulse region should be assumed to extend to a distance from ground zero where the peak overpressure associated with the blast wave was 6 psi;
- The effective resuspension factor should be applied to exposures of participants in the thermal-pulse region that occurred within a day after a detonation, unless it is known that resuspended fallout was dispersed by winds within that time.

Blast-Wave Region

- An effective resuspension factor of $10^{-4}$ $m^{-1}$ should be assumed;
- The blast-wave region should be assumed to extend from the thermal-pulse region to a distance from ground zero where the peak overpressure associated with the blast wave was 2 psi, unless there were reports of high levels of resuspended dust at greater distances at times shortly after a detonation;
- The effective resuspension factor should be applied to exposures of participants in the blast-wave region that occurred within 5 hours after a detonation, unless it is known that resuspended fallout was dispersed by winds within that time.

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