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Nevada
Environmental
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Project

Methodology for Calculating Guideline Concentrations for Safety Shot Sites

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Environmental Restoration
Division

U.S. Department of Energy
Nevada Operations Office

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DOE Nevada Operations Office
Las Vegas, Nevada

June 1997

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List of Acronyms and Abbreviations

Ac	Actinium
AIHC	American Industrial Health Council
ALARA	As low as reasonably achievable
Am	Americium
AMAD	Activity median acrodynamic diameter
CEDE	Committed Effective Dose Equivalent
cm	Centimeter(s)
d/yr	Day(s) per year
DCF	Dose conversion factor(s)
DL	Dilution length
DOE	U.S. Department of Energy
DSR	Dose/source ratio
DU	Depleted uranium
EDE	Effective dose equivalent
EPA	Environmental Protection Agency
ETF	Environmental transport factor
Fd	Depth factors
g	Gram(s)
g/cm^3	Gram(s) per cubic centimeter
g/d	Gram(s) per day
g/m^3	Gram(s) per cubic meter
g/yr	Gram(s) per year
h/d	Hour(s) per day
ha	Hectare(s)
ICRP	International Commission on Radiological Protection
keV	Kiloelectron volt(s)
L	Liter(s)
L/d	Liter(s) per day
m	Meter(s)
m/s	Meter(s) per second
m/y	Meter(s) per year
m^2	Square meter(s)

m^2/s	Square meter(s) per second
m^3	Cubic meter(s)
m^3/d	Cubic meter(s) per day
MeV	Megaelectron volts
mg	Milligram(s)
mg/d	Milligram(s) per day
mrem/pCi	Millirem(s) per picoCurie
mrem/yr	Millirem(s) per year
NAFR	Nellis Air Force Range
NCRP	National Council on Radiation Protection and Measurements
Np	Neptunium
NTS	Nevada Test Site
Pa	Protactinium
Pb	Lead
pCi	PicoCurie(s)
pCi/cm^2	PicoCurie(s) per square centimeter
pCi/cm^3	PicoCurie(s) per cubic centimeter
pCi/g	PicoCurie(s) per gram
pCi/L	PicoCurie(s) per liter
pCi/yr	PicoCurie(s) per year
Pu	Plutonium
R	Radius
Ra	Radium
RESRAD	Residual Radioactivity (computer code)
Rn	Radon
SF	Source factor
T	Depth
Th	Thorium
TTR	Tonopah Test Range
U	Uranium
WLM	Working level month
WU	Weapons grade uranium
μm	Micrometer(s)

1.0 Introduction

Residual plutonium (Pu), with trace quantities of depleted uranium (DU) or weapons grade uranium (WU), exists in surficial soils at the Nevada Test Site (NTS), Nellis Air Force Range (NAFR), and the Tonopah Test Range (TTR) as the result of the above-ground testing of nuclear weapons and special experiments involving the detonation of plutonium-bearing devices. The special experiments (referred to as "safety shots") involving plutonium-bearing devices were conducted to achieve the following objectives:

- Study the behavior of Pu as it was being explosively compressed.
- Ensure that the accidental detonation of the chemical explosive in a production weapon would not result in criticality.
- Evaluate the ability of personnel to manage large-scale Pu dispersal accidents.
- Develop criteria for transportation and storage of nuclear weapons.

The first set of safety shots were called "hydrodynamic" or "equation of state" tests. Twenty-two such tests were conducted above-ground at the GMX location in Area 5 (Stannard, 1988). Numerous tests were conducted to determine if a criticality could be produced from accidental detonations of the chemical explosives in production weapons. The largest tests carried out on the surface were in Project 56 in Area 11 in what is now known as Plutonium Valley. One nuclear device was detonated in 1956, resulting in a slight nuclear yield. The final, large surface experiment was conducted as Project 57 in Area 13, just off the NTS (Stannard, 1988). Experiments performed to evaluate cleanup and weapons-handling issues consisted of operations Roller Coaster; Double Tracks; and Clean Slates 1, 2, and 3 (Shreve, 1964).

All of the safety shot sites where these tests were conducted are contaminated with Pu. In addition, most are contaminated with trace quantities of DU. The Project 56 safety shot site in Plutonium Valley is contaminated with trace quantities of WU. At the present time, these sites do not pose a health threat to either workers or the general public because they are under active institutional control. All sites are located in areas of restricted access, and inadvertent human intrusion is deterred by the use of fences and warnings. However, because the half-lives of Pu and DU isotopes are very long, (greater than 10,000 years), residual contamination may pose a long-term health hazard if it were not remediated. Members of the public could acquire the land for residential, agricultural, and industrial purposes following a loss of institutional control. The

Department of Energy (DOE) is committed to remediating the safety shot sites so that radiation exposures to members of the public, both now and in the future, will be maintained within the established limits and be as low as reasonably achievable (ALARA).

Remedial actions of the safety shot sites will follow the recommendations established in DOE Order 5400.5, *Radiation Protection of the Public and the Environment* (DOE, 1993). Remediation requires calculation of a guideline concentration for the plutonium, uranium (U), and their decay products that are present in the surface soil at the safety shot sites. A guideline is defined as a radionulcide concentration that, given appropriate use scenarios and site parameters, will reasonably ensure that dose limits to the average individual in the critical population will not be exceeded. The DOE has established generic cleanup guidelines for radium and thorium in soil in DOE Order 5400.5 (DOE, 1993). However, cleanup guidelines for all other radionuclides must be derived on a site-specific basis.

The guideline is based upon a radiation dose criterion of 100 millirems per year (mrem/yr). The radiation dose is defined as the effective dose equivalent from external radiation plus the committed effective dose equivalent from internal radiation (DOE, 1993). The 100 mrem/year dose criterion is the DOE primary standard dose rate to ensure protection to members of the public. This criterion includes the dose contribution for all significant pathways and sources combined, excluding the natural background. This dose rate complies with the recommendation for controlling dose to members of the public by the International Commission on Radiological Protection (ICRP) (1991).

This document presents the methodology for calculating guideline concentrations of weapons grade plutonium, weapons grade uranium, and depleted uranium in surface soils at the safety shot sites. The methodology used in calculating the guideline concentrations is consistent with the procedures and guidance provided in DOE/CH-8901, *A Manual for Implementing Residual Radioactive Material Guidelines* (Gilbert et al., 1989). DOE Order 5400.5 prescribes that DOE/CH-8901 be used for deriving specific property guidelines for allowable levels of residual radioactive material from basic dose limits (DOE, 1993). Emphasis is placed on obtaining site-specific data for use in calculating dose to potential residents from the residual soil contamination. Default data values listed in the open scientific literature, and recommendations of the National Council on Radiation Protection and Measurements (NCRP), the ICRP, and the

United States Environmental Protection Agency (EPA) are used when site-specific data is not available. The topics addressed in presenting the methodology include:

- Dose criteria used to establish the guideline
- Radiological source terms at safety shot sites
- Exposure pathways identified with the remediated safety shot sites
- Models used in analyzing the exposure pathways
- Mathematical expressions of the Residual Radioactivity (RESRAD) code used in calculating guideline concentration
- Exposure scenarios to be investigated and analyzed for the safety shot sites

2.0 Dose Criteria

The primary dose limits for members of the public from all Department of Energy activities, including remedial actions, are established in Chapters II and IV in DOE Order 5400.5 (DOE, 1993). The primary dose limit is expressed as a committed effective dose equivalent, a term developed by the ICRP for their risk-based system, which requires the risk-weighted summation of doses to various tissues and organs of the body. The exposure of members of the public to radiation sources as a consequence of all routine DOE activities must not cause, in a year, an effective dose equivalent greater than 100 mrem. This is defined by the DOE as their basic dose limit for protection to members of the public. This is the dose limit used in establishing guideline concentrations. The basic dose limit is an annual limit for members of the public who are assumed to participate in worst-case exposure scenarios. Assessments of lifetime dose to an individual and collective dose to a population are not required.

Chapter IV of DOE Order 5400.5 presents radiological protection requirements and guidelines for cleanup of residual radionuclides in soil (DOE, 1993). The basic dose limit resulting from exposures to residual radionuclides in soil is a prescribed standard from which limited quantities that can be monitored and controlled are derived. It is also specified in terms of the effective dose equivalent. The basic dose limit is used for deriving guidelines for residual concentrations of radionuclides in soil. A guideline is a concentration of a radionuclide in soil that is acceptable for property use without restrictions due to residual radioactive material. DOE Order 5400.5, Chapter IV, states, "Residual concentrations of radioactive material in soil are defined as those in excess of background concentrations averaged over an area of 100 square meters (m^2)" (DOE, 1993). Guidelines for thorium and radium in soil have also been established in DOE Order 5400.5 (DOE, 1993). Guidelines for residual concentrations for other radionuclides in soil have to be derived from the basic dose limit by means of an environmental pathway analysis using specific property data where available. Procedures for these derivations are given in DOE/CH-8901 and implemented in the RESRAD computer code (Gilbert et al., 1989; Yu et al., 1993a). The following sections describe how the environmental pathways are analyzed by the RESRAD code in establishing guideline concentrations for safety shot sites.

2.1 Dose

It may be helpful to explain the term "dose" and describe how it is used in the context of this document. Dose is a measurement of the cancer and genetic risk to a tissue, organ, or individual due to the radiation absorbed. The Committed Effective Dose Equivalent (CEDE) is the dose calculated to demonstrate that the guideline concentration complies with DOE Order 5400.5. The CEDE is the ionizing energy absorbed in tissue over a period of 50 years, resulting from uptakes and exposure to radioactive material in a year and modified using risk factors that relate organ and tissue risk to malignant and hereditary diseases as well as to the risk from a uniform whole-body external exposure. The dose due to exposure to external radiation or from an intake of a radionuclide can never be measured directly, nor is it easily calculated. For example, the physiochemical behavior of a radionuclide attached to a soil particle inhaled into the lungs (and its distribution in and clearance through and out of the body) is related to the chemical form of the soil particle, the decay rate of the radionuclide, the type of decay the radionuclide undergoes, and the activity median aerodynamic diameter (AMAD) of the particle. The AMAD relates a particle's behavior in air to a reference standard sphere of 1 micrometer (μm) diameter. The dose is also dependent on the age, physiology, sex, weight of tissue and organs, and metabolic rate of the individual who inhaled the particle. All of these attributes are independent of each other. Complex matrices of differential equations are required to describe resultant dose and how the radioactive material is distributed throughout the body.

Dose conversion factors (DCFs) have been published to simplify the calculation of the dose due to an individual's exposure to external radiation and to internal radiation from the intake of radioactive materials. A DCF for external exposure converts the concentration of a radionuclide in an environmental media, such as soil, to an individual's dose rate. A DCF for an internal dose is the ratio of the dose to an individual from the quantity of a radionuclide that was inhaled or ingested. The external DCF considers the elemental composition of the media, the dimensions or extent of the media, and its density. The internal DCFs consider the chemical form of the soil particle or material associated with the radionuclide and can be adjusted for different particle size distributions and chemical forms. Physiological attributes affecting dose are assumed to be for a standard man (ICRP, 1974). The DCFs are derived from models recommended by the ICRP (1977a, 1977b, 1979-1982) and have been adopted by the federal government for all agencies having regulatory responsibilities for use of radioactive material in the public domain (Eckerman et al., 1988). These same DCFs are used in the RESRAD code for calculating dose.

3.0 Radiological Source Term

Calculating the dose to a member of the public from residual contamination requires definition of a contaminated zone. This is the region within which radionuclides are present in above-background concentrations, and it is the common source term and starting point for all exposure pathway analysis. The derivation of soil cleanup concentrations is based upon idealized contaminated regions of cylindrical shape within which radionuclides are assumed to be uniformly distributed.

The surface soils on the safety shot sites are contaminated with weapons grade plutonium and trace quantities of depleted or weapons grade uranium. The concentration of the plutonium and depleted uranium on the soil surface varies over multiple orders of magnitude at each safety shot site. The distribution of radionuclides is not uniform. However, most of the contamination exists within an inch of the surface, and virtually all of the contamination is in the top two inches. The area of contamination for the safety shot sites varies from about 15 acres to greater than 500 acres.

The dose to a hypothetical member of the public residing on a remediated safety shot site is calculated by assuming that the entire site area is uniformly contaminated. The dose to the hypothetical receptors is calculated by assuming that all soil areas where the plutonium-239/240 (Pu-239/240) concentration of ≥200 picoCuries per gram (pCi/g) is remediated to a concentration of 200 pCi/g. The mean Pu-239/240 concentration is then calculated for the contaminated area based upon this assumption. The dose to the hypothetical receptor is calculated based upon the mean Pu-239/240 concentration. This assumption is conservative; experience has demonstrated that remediation reduces the Pu-239/240 concentrations in soil that exceeded 200 pCi/g to a level significantly less than 200 pCi/g.

Two types of radiological source terms predominate at the safety shot sites. They are depleted uranium and weapons grade plutonium. Each of the two predominate source terms consists of a mixture of radionuclides. The Project 56 safety shots used weapons grade plutonium and uranium. All other safety shots consisted of weapons grade plutonium and depleted uranium. Weapons grade uranium is assumed to be U-235. The depleted uranium source term assumed in this methodology is that recommended in *Health Physics Manual of Good Practices for Uranium Facilities* (Rich, 1988). This depleted uranium source term will be used in calculating safety shot guidelines for all sites except Project 56 in area 11. The composition of depleted uranium is listed in Table 3-1.

Table 3-1
Abundance by Mass and Radioactivity for Depleted Uranium

Isotope	**Abundance by Mass** (grams [g] isotope/100 g uranium)	**Abundance by Radioactivity** (picoCuries [pCi] of isotope per 100 pCi uranium)
U-238[a]	99.75	90.13
U-235	0.25	14.60
U-234	0.0005	8.42

[a]Uranium

There are significant differences in the composition of the isotopic mixture for weapons grade plutonium. The primary difference between the weapons grade plutonium mixtures is the concentration of americium (Am)-241. The Am-241 is produced as the decay product of Pu-241, a typical component of weapons grade plutonium. The standard radionuclide mixture used in calculating guidelines for safety shot sites is based upon a 33-year decay time of standard weapons grade plutonium, corrected for the activity of Am-241 measured at the safety shot site. This decay time was chosen because it is representative of the time elapsed since most of the safety shots were performed. The standard isotopic composition for weapons grade plutonium for safety shot sites is indicated in Table 3-2.

Table 3-2
Radiological Source Term for Safety Shot Sites

Isotope	**Abundance by Radioactivity** (pCi of isotope per 100 pCi of Pu-239/240)
Am-241	7.14
Pu-238	0.77
Pu-239	91.3
Pu-240	8.69
Pu-241	45.2
Pu-242	0.000184
U-238	0.024

This isotopic mixture will be used as the standard for weapons grade plutonium contamination for calculating guideline concentrations. Operational knowledge of the radiological source term for a specific safety shot site may indicate that a different weapons grade plutonium mixture would be more appropriate than the standard isotopic mixture. A different radionuclide mixture may be used in calculating the guideline if, and only if, evidence from soil sample analysis and *in situ* measurements of the surface soil supports the modified isotopic mixture.

As previously stated, the RESRAD code is used for assessing dose from residual contamination and in calculating guideline concentrations (Yu et al., 1993a). The RESRAD code defines two categories of radionuclides, principal and associated radionuclides. A principal radionuclide is a radionuclide with a half-life greater than six months. All of the radionuclides listed in Tables 3-1 and 3-2 are principal radionuclides. Radionuclides with a half-life of six months or less are treated by the RESRAD code as associated radionuclides. The radionuclides "associated" with a principal radionuclide consist of all decay products down to, but not including, the next principal radionuclide in the decay chain. The RESRAD code requires that only the concentration of the principal radionuclides be identified when defining the contaminated zone. RESRAD assumes that all associated radionuclides are in secular equilibrium with their principal radionuclide in the contaminated zone at the location of human exposure.

4.0 Exposure Pathways

Each possible route that may lead to a radiation dose from the safety shot soil contamination is known as a radiation exposure pathway. Potential pathways are identified in Table 4-1. The three major headings correspond to three exposure pathways by which radiation may interact with human tissues and organs. In the first pathway, exposure is by external radiation from radionuclides outside the body. A fraction of the radiation emitted from depleted uranium, weapons grade plutonium, and their decay products is sufficiently penetrating (i.e., gamma rays and high energy x-rays) to expose an individual in the vicinity of the contaminated soil to an external radiation dose. In the second and third pathways, exposure is by internal radiation from radionuclides that are inhaled or ingested.

For each exposure pathway, radionuclides can migrate from the soil surface to a location where the dose receptor may be exposed. Each way in which a radionuclide may migrate to the exposure location is an environmental pathway, and the environmental pathways considered in calculating site specific guidelines are also listed in Table 4-1. In addition, each major pathway may have associated subpathways, for example, ingestion. The ingestion pathway is a major pathway with five subpathways including the ingestion of milk, beef, water, plant foods, and soil.

Table 4-1
Potential Pathways of Exposure for Safety Shot Sites

External radiation Ground Volume source*
Air Dust Radon and radon decay products
Inhalation Dust* Radon and radon decay products*
Ingestion Food Plant foods (vegetables, grains, and fruits)* Meat* Milk* Water Groundwater (well)* Soil*

*Pathway used to derive site-specific soil guidelines

The schematic representation of RESRAD environmental and exposure pathways is illustrated in Figure 4-1. Minor pathways for on-site exposure are not taken into account in deriving soil guidelines because the dose contribution from these pathways is expected to be insignificant. An example of a minor pathway is external radiation from a surface layer created by redeposition of airborne radionuclides resuspended by the wind. The external radiation from the redeposited soil would be very minor in comparison to the external radiation from the residual radioactive material in its original location. Another example of a minor pathway is the external radiation dose from contaminated water and food. The dose contribution from the external radiation is insignificant in comparison to the internal dose from ingesting the water and food.

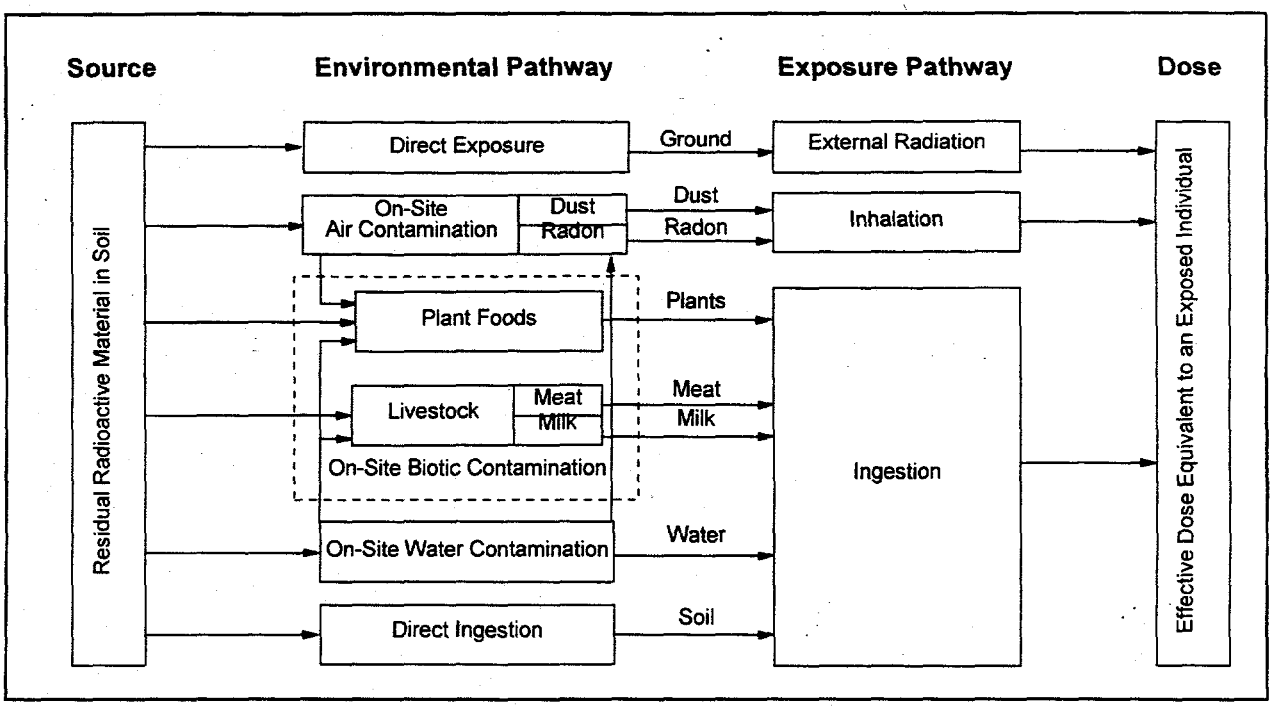

Figure 4-1
Schematic Representation of RESRAD Pathways for Clean Slate Sites

Another minor pathway not considered is the external radiation dose from airborne dust and radon decay products because it is orders of magnitude smaller than the inhalation dose from dust (Gilbert et al., 1983).

As shown in Figure 4-1, the only radiological source term considered in this methodology is the residual radioactive material in surface soil. Exposure from contamination in groundwater due to the testing of underground nuclear devices is not considered to be an environmental pathway. In this methodology, the only radionuclides contributing to the groundwater environmental pathway are from the contaminated surface soil on the safety shot sites.

Section 4.1 discusses the mathematical expressions used in calculating the guideline concentrations. These expressions as well as the nomenclature and models used in describing the environmental pathway models in this document are the same as those adopted in the RESRAD User's Manual (Yu et al., 1993a). The subsequent sections discuss each exposure pathway.

4.1 Methodology for Calculating Guideline Concentrations in Soil

The dose contribution from an environmental pathway is calculated by means of dose/source ratios (DSRs) that are expressed in terms of three factors: dose conversion factors, environmental transport factors (ETFs), and source factors (SFs). The definitions and use of these factors for deriving soil guidelines are described in this section. The detailed models and formulas used in calculating the factors for each exposure pathway are given in the RESRAD User's Manual (Yu et al., 1993a).

4.1.1 Dose Conversion Factors

A dose conversion factor is the dose per unit contamination for the external exposure pathway (millirems per year per picoCuries per cubic centimeters [pCi/cm^3]) or the dose per unit intake for ingestion and inhalation exposure pathways. It is expressed mathematically as:

$$DCF_{ix} = H_{E,ix} / E_{ix} \,, \qquad (1)$$

where:

DCF_{ix} = the dose conversion factor from the *i*th principal radionuclide and its associated decay products for exposure pathway x;

$H_{E,ix}$ = the annual effective dose equivalent resulting from exposure to external radiation from the *i*th principal radionuclide and its associated decay products (mrem/yr) or the committed effective dose equivalent (the dose over the following 50 years due to an intake in one year) resulting from the amount of the *i*th principal radionuclide and its associated decay products inhaled or ingested in one year (mrem/yr); and

E_{ix} = the exposure parameter for the *i*th principal radionuclide (concentration of the *i*th principal radionuclide in a standard source [for external radiation pathways] or the annual quantity of the *i*th principal radionuclide inhaled or ingested [for internal radiation pathways]) (pCi/cm^3 for external radiation from the contaminated zone; picoCuries per year [pCi/yr] for internal radiation from inhalation or ingestion).

An internal DCF for any radionuclide includes the contribution from ingrowth following ingestion or inhalation. The internal DCF for a principal radionuclide also includes the contribution from inhalation or ingestion of its associated decay products along with the principal radionuclide. The additional contribution is significant for decay products with physical half-lives that are not small compared to their biological half-life. The DCF for external radiation for a principal radionuclide includes the dose from all of its decay products which are assumed to be in secular equilibrium.

Dose conversion factors for external radiation from the contaminated zone, internal radiation from inhalation of airborne radionuclides, internal radiation from ingestion, and internal radiation from inhalation of radon and its decay products are discussed in the following sections of this document. The DCFs used in calculating guideline concentrations are the latest recommendation from the federal government and are found in Federal Guidance Report No. 11 (Eckerman et al., 1988). These DCFs are the default values stored in the RESRAD code. The DCFs pertinent to the source terms at the safety shot sites are listed in Tables 4-2, 4-5, and 4-6. Additional information regarding the DCFs may be found in Sections 2.3 and 3.2 of the RESRAD User's Manual (Yu et al., 1993a).

4.1.2 Environmental Transport Factors

An environmental transport factor is a time-dependent ratio that adjusts the concentration of the contaminant in the soil for radioactive decay of its parent radionuclide at the initial concentration and for other time-dependent parameters that are dependent on the environmental pathways being analyzed. The general mathematical expression for the ETF is:

$$ETF_{ij,pq}(t) = E_{ij,pq}(t)/S_i(0) \times SF'_{ij,pq}(t) \qquad (2)$$

where:

$ETF_{ij,pq}(t)$ = the environmental transport factor for the *j*th radionuclide transported through the *pq*th environmental pathway as a result of the decay of the initially existent radionuclide *i* in the soil at time t;

$E_{ij,pq}(t)$ = the exposure parameter value at time *t* for the *j*th radionuclide (or its radiation) transported through the *pq*th environmental pathway as a result

Table 4-2
Effective Dose Equivalent Conversion Factors (DCF_{i1}) for External Gamma Radiation from Contaminated Ground for Isotopes Pertinent to Clean Slate Sites

Isotope	Surface Factors[a] (mrem/yr)/(pCi/cm^2)[c]	Volume Factors[b] (mrem/yr)/(pCi/cm^3)	
		ρ_b = 1.0 (g/cm^3)[d]	ρ_b = 1.8 (g/cm^3)
Pb-210+D[e]	3.01 x 10^{-3}	4.87 x 10^{-3}	2.31 x 10^{-3}
Ra-226+D	1.68	1.55 x 10^{-1}	8.56
Ra-228+D	9.10 x 10^{-1}	8.18	4.51
Ac-227+D	4.37 x 10^{-1}	2.76	1.52
Th-228+D	1.45	1.33 x 10^{1}	7.36
Th-229+D	3.60 x 10^{-1}	2.20	1.21
Th-230	9.07 x 10^{-4}	2.11 x 10^{-3}	1.03 x 10^{-3}
Th-232	6.66 x 10^{-4}	1.35 x 10^{-3}	6.04 x 10^{-4}
Pa-231	3.58 x 10^{-2}	2.21 x 10^{-1}	1.21 x 10^{-1}
U-232	1.03 x 10^{-3}	2.19 x 10^{-3}	1.01 x 10^{-3}
U-233	5.00 x 10^{-4}	1.40 x 10^{-3}	7.12 x 10^{-4}
U-234	8.07 x 10^{-4}	1.58 x 10^{-3}	6.97 x 10^{-4}
U-235+D	1.90 x 10^{-1}	8.94 x 10^{-1}	4.90 x 10^{-1}
U-236	7.33 x 10^{-4}	1.35 x 10^{-3}	5.80 x 10^{-4}
U-238+D	2.59 x 10^{-2}	1.27 x 10^{-1}	6.97 x 10^{-2}
Np-237+D	2.68 x 10^{-1}	1.61	8.90 x 10^{-1}
Pu-238	8.58 x 10^{-4}	1.56 x 10^{-3}	6.65 x 10^{-4}
Pu-239	3.78 x 10^{-4}	8.14 x 10^{-4}	3.76 x 10^{-4}
Pu-240	8.20 x 10^{-4}	1.48 x 10^{-3}	6.35 x 10^{-4}
Pu-241+D	3.94 x 10^{-6}	1.88 x 10^{-5}	1.05 x 10^{-5}
Pu-242	6.82 x 10^{-4}	1.24 x 10^{-3}	5.29 x 10^{-4}
Am-241	2.99 x 10^{-2}	4.79 x 10^{-2}	2.58 x 10^{-2}

[a]Surface Factors represent infinite thinness
[b]Volume factors represent infinite depth
[c]pCi/cm^2 - PicoCurie(s) per square centimeter
[d]g/cm^3 - Gram(s) per cubic centimeter
[e]Includes Daughters

of the decay of the initially existent radionuclide i in the soil (pCi/cm^3 for external radiation from the contaminated zone; pCi/yr for internal radiation). For external radiation, dust inhalation, and soil ingestion pathways, $E_{ij,pq} = E_{jp}$; for ingestion of plant food, meat, and milk contaminated from root uptake and foliar deposition $E_{ij,pq} = E_{jpq}$; for ingestion of meat and milk when the environmental pathway is livestock ingestion of contaminated soil, $E_{ij,pq} = E_{jpq}$; and for the drinking water pathway, $E_{ij,pq} = E_{ijp}$;

p = the index label for environmental pathways;

q = the index label for the component of the environmental pathway p;

$S_i(0)$ = the average concentration of the ith principal radionuclide in a uniformly contaminated zone at time 0 (pCi/g); and

$SF'_{ij,pq}(t)$ = an adjusting factor to modify the soil concentration. For external radiation, dust inhalation, and soil ingestion pathways, $SF'_{ij,pq}(t) = SF'_{ij,}(t)$;$SF'_{ij,}(t)$ is the source factor which, when multiplied by $S_i(0)$, will give the soil concentration of radionuclide j at time t, $S_{j,}(t)$. For the ingestion of plant food, meat, and milk pathways when the environmental pathway is root uptake and foliar deposition, $SF'_{ij,pq}(t) = SF_{ij,}(t)$; when the transport is through irrigation $SF'_{ij,pq}(t) = 1$. When the exposure pathway is ingestion of meat and milk when the environmental pathway is livestock ingestion of contaminated water, $SF'_{ij,pq}(t) = 1$, and $SF'_{ij,pq}(t) = Sf_{ij,}(t)$ when the environmental pathway is through the ingestion of contaminated soil. When the exposure pathway is drinking water, ingestion $SF'_{ij,pq}(t) = 1$.

The exposure parameter for external radiation from the contaminated zone is the concentration of the jth principal radionuclide and its decay products that are in the ground, adjusted for occupancy and the size and depth of the contaminated zone by means of multiplying factors. The exposure parameter for internal radiation pathways is the annual quantity of the jth principal radionuclide that is inhaled or ingested after migrating through the pqth environmental pathway. There are only two internal exposure pathways (inhalation and ingestion); several environmental pathways can contribute to each.

4.1.3 Source Factors

The time dependence of dose/source ratios resulting from radioactive ingrowth and decay and infiltrating and leaching is taken into account by introducing source factors (SFs), $SF_{ij}(t)$. The RESRAD code categorizes radionuclides into two groups: those with half-lives greater than six months (principal radionuclides) and those with half-lives of six months or less (associated radionuclides). It is assumed that the associated radionuclides are in secular equilibrium with their principal radionuclide and that the leach rate of the associated radionuclide is the same as the leach rate of their principal radionuclides. These assumptions are conservative and will slightly over-estimate the dose while greatly simplifying calculational methods. Because of this simplifying assumption, only the SFs for the principal radionuclides need to be calculated. A general expression for a SF is the following time dependent ratio:

$$Sf_{ij,}(t) = S_{ij}(t)/S_i(0) \tag{3}$$

where:

$Sf_{ij,}(t)$	=	the source factor (dimensionless);
$S_{ij}(t)$	=	the concentration at time t of the jth principal radionuclide remaining in the contaminated zone after leaching and ingrowth from the ith principal radionuclide, if $j \neq i$ (pCi/g); or the concentration at time t of the ith principal radionuclide remaining in the contaminated zone after leaching and decaying (or transforming), excluding contributions from ingrowth from other radionuclides, if $j = i$ (pCi/g); and
$S_i(0)$	=	the initial concentration of the ith principal radionuclide in the contaminated zone (pCi/g).

Formulas for calculating source factors are given in Appendix G of the RESRAD User's Manual (Yu et al., 1993a).

4.1.4 Dose/Source Concentration Ratios

The dose/source concentration ratios are calculated by expressing them as the product of the DCFs, ETFs, and SFs. The factored expression for a dose/source ratio is:

$$DSR_{ip}(t) = \Sigma_{(j)}(DCF_{j,x(p)} \times BRF_{i,j}) \times \Sigma_{(q)}(ETF_{ij,pq}(t) \times SF'_{ij,pq}(t)) \tag{4}$$

where:

$DSR_{ip}(t)$	=	the dose/source ratio for the ith radionuclide and exposure pathway p at time t;

$DCF_{j,x(p)}$ = the dose conversion factor for the *j*th principal radionuclide and *x*(p)th exposure pathway ([mrem/year]/[pCi/cm^3] for external radiation from the contaminated zone; mrem/pCi for internal radiation from ingestion or inhalation of radionuclides);

$BRF_{i,j}$ = a branching factor (dimensionless) that is the fraction of the total decay of radionuclide *i* that results in the ingrowth of radionuclide *j*;

$ETF_{ij,pq}(t)$ = $ETF_{jp}(t)$, environmental transport factor for the *j*th principal radionuclide at time *t*, when the exposure pathway is for external radiation from the contaminated zone, it is expressed in grams per cubic centimeters (g/cm^3); for internal radiation from dust inhalation and soil ingestion it is expressed in grams per year (g/yr). For the plant, meat, and milk ingestion exposure pathways, it is the environmental transport factor for the *j*th principal radionuclide originating from the decay of the *i*th principal radionuclide for the *q*th component of the *p*th environmental pathway at time *t* (g/yr). For the ingestion of drinking water, it is equivalent to $ETF_{ij,p}(t)$, the environmental transport factor for the *j*th principal radionuclide originating from the decay of the *i*th principal radionuclide for the *q*th component of the *p*th environmental pathway at time *t* (g/yr);

$SF'_{ij,pq}(t)$ = $SF_{ij}(t)$, factor for ingrowth and decay and leaching of the *j*th principal radionuclide at time *t* from the *i*th principal radionuclide initially present (dimensionless) when the exposure pathway is external radiation, dust inhalation, or soil ingestion. For plant ingestion, $SF'_{ij,pq}(t)$ is equivalent to $SF_{ij}(t)$ when the environmental pathways are root uptake and foliar deposition. $SF'_{ij,pq}(t) = 1$ when the environmental pathway is irrigation. $SF'_{ij,pq}(t)$ is equivalent to $SF_{ij}(t)$ when the environmental pathway is meat and milk ingestion and the environmental component pathway is root uptake, foliar deposition, and livestock ingestion of soil, and it is 1 when the environmental pathway is irrigation or livestock ingestion of drinking water. $SF'_{ij,pq}(t)$ is 1 when the environmental pathway is ingestion of drinking water;

x(p) = the index label for exposure pathways, which is a function of the environmental pathway p (when p is the external radiation from the ground, x[p] = 1; when the environmental pathway is inhalation of dust and radon, x[p] = 2; and for ingestion of plants, meat, milk, fish, water, and soil, respectively, x[p] = 3);

p = the index label for environmental pathways;

q = the index label for environmental pathway components. Some pathways have several components. For example, for milk and meat ingestion, there are five components: root uptake, foliar deposition, irrigation of the food crops used as fodder, ingestion of drinking water by livestock, and livestock ingestion of soil. For some environmental pathways, there is only one component. Examples are external radiation, inhalation of resuspended soil, ingestion of drinking water, and ingestion of contaminated soil; and

i,j = the index labels for principal radionuclides, where *i* refers to radionuclides that exist initially at time *t*, and *j* refers to radionuclides in the decay chain of radionclide *i*.

4.2 External Radiation Pathways

Gamma radiation and high energy x-rays emitted from radionuclides distributed throughout the contaminated zone are the only external radiation pathways considered in calculating soil guidelines. Nearly all of the energy of the electrons and beta particles emitted from the radionuclides in the soil is absorbed in the soil or in the first few inches of air. In addition, the dose contribution from electrons and beta particles is primarily restricted to the skin. The overall health risk due to a dose equivalent received by the skin is about two percent of the risk when the same dose equivalent is distributed uniformly over the whole body (ICRP, 1991). Therefore, their contribution to the external dose is negligible, and can safely be ignored.

In addition to the emission of photons and beta particles, some radionuclides emit neutrons when they undergo spontaneous fission. The uranium and plutonium isotopes in the safety shot soil undergo spontaneous fissions at an extremely low rate. The fraction of disintegrations that result in a spontaneous fission of Pu-239, for example, is approximately 4.4E-12. The contribution from neutrons to the external radiation from depleted uranium and weapons grade plutonium source terms is not significant in comparison to the gamma radiation (NCRP, 1976). Therefore, the contribution to the external radiation dose from neutrons is not considered in this methodology.

The contribution to the effective dose equivalent from the external ground radiation pathway to the *i*th principal radionuclide at time *t* following remediation is given by the dose/source ratio, DSR_{i1} (t). This ratio is expressed as the sum of the product of the dose conversion factor (DCF_{j1}), the environmental transport factor (ETF_{j1}), and the source factor (SF_{ij}). The DCFs used in calculating the external ground radiation pathway for the radionuclides anticipated for safety shot sites are listed in Table 4-2. Models and formulas for calculating the ETFs, SFs, and quantitative details on the mathematical models used in calculating the external radiation pathway are presented in Appendix A of the RESRAD User's Manual (Yu et al., 1993a).

4.2.1 Dose Conversion Factors for External Radiation Pathway

The dose conversion factor, DCF_{i1}, for the external ground radiation pathway is the annual effective dose equivalent received from exposure to radiation from the *i*th principal radionclide present at the unit concentration in a uniformly contaminated zone of infinite depth and lateral extent. The radiation field is assumed to be equal to the radiation level at a distance of 1 meter (m) above the ground surface. The DCFs for the standard source in RESRAD are for an idealized volume source where the contamination is of infinite depth and lateral extent, assumed densities of 1.0 and 1.8 g/cm^3, and were calculated using the methods of Kocher and Sjoreen (1985) and Chen (1991). External radiation dose rates for other densities are obtained by linear interpolation or extrapolation of the log (DCF) by the RESRAD code. The effective dose equivalent conversion factors (DCF_{i1}) for external gamma radiation from the radiological contamination in the ground that are used in calculating soil cleanup guidelines are listed in Table 4-2. The DCF_{i1} conversion factors listed in Table 4-2 are the same as those used in the RESRAD code.

4.2.2 Environmental Transport Factors for External Radiation Pathway

The environmental transport factor (ETF_{i1}) for the external ground radiation pathway is the ratio of the effective dose equivalent for the actual source to the effective dose equivalent for the standard source, multiplied by an occupancy and shielding factor. The standard source is a contaminated zone of infinite depth and lateral extent with no cover. The actual source is approximated by a cylindrical contaminated zone of radius (R) and depth (T). The RESRAD code calculates R from the area supplied by the code user. The contamination depth is also supplied directly by the RESRAD code user. The site area and depth of contamination are derived from *in situ* gamma spectroscopy measurements taken at the safety shot site.

The parameters that affect the external radiation pathway environmental transport factors are the area of the contamination zone, the thickness of the zone, the bulk density of the soil, and the occupancy factor. Each of these parameters is defined by the RESRAD code user. The RESRAD code applies these values with code-specified parameters to calculate ETF_{i1} in accordance with the methodology of Napier et al. (1984). The mathematical expressions used by the RESRAD code in calculating ETF_{i1} are described in Appendix A of the RESRAD Manual (Yu et al., 1993a). The DCF values for the radionuclides pertinent to safety shot sites are listed in Table 4-2.

The area of the contaminated zone is one of the most significant parameter values affecting the guideline. The area of the contamination is calculated applying site-specific data gathered during characterization activities. *In situ* measurements of the photons emitted from the soil contaminants are used to create a map of the contaminated area.

The RESRAD code applies the site area in calculating an area factor. This is a dimensionless parameter. The area factor is calculated by linear interpolation using the contaminated zone area, a user input parameter, and the values listed in Table 4-3. The area factor calculated is for a circular-area-equivalent contaminated zone. Details about how the area factor is calculated by RESRAD can be found in Appendix A of the RESRAD User's Manual (Yu et al., 1993a).

Table 4-3
Area Factors for External Gamma Radiation from Contaminated Ground

Contaminated Area (m^2)	Radius[a] (m)	Area Factor,[b] FA_1
1	0.56	0.016
25	2.8	0.4
100	5.6	0.55
500	13	0.8
≥1,200	20	1.0

[a]Radius for a circular contaminated area
[b]Intermediate values may be obtained by linear interpolation.

A second parameter affecting the external radiation dose rate is the thickness of the contamination zone. The thickness of the contaminated zone, (e.g., the depth of the soil contamination) is calculated from *in situ* gamma spectroscopy measurements taken at the safety shot site. The external radiation dose rate increases with the thickness of the contaminated zone until the thickness is sufficient to shield a dose receptor from radiation emitted by the radionuclides at greater depths. For example, the external dose rate as a function of the thickness of the contamination zone from 100 pCi/g of DU and 100 pCi/g of Pu-239/240 in weapons grade plutonium at a hypothetical large area site during the first year following remediation is shown in Table 4-4.

Table 4-4
External Dose Rate as a Function of Contaminated Thickness for 100 pCi/g DU and 100 pCi/g Pu-239/240

Depth of Contamination Zone Centimeters (cm)[a]	**Dose Rate** (mrem/yr)	
	100 pCi/g DU	**100 pCi/g Pu-239/240**
0.1	0.34	0.025
0.5	1.39	0.079
1.0	2.28	0.116
5.0	5.82	0.241
10.0	8.00	0.268
15.0	9.05	0.272

[a]Centimeter(s)

The data in Table 4-4 show that the dose rate from the DU is increasing with contamination zone thickness through a depth of 15 cm. At a depth of 0.1 cm, the external dose rate from the DU is about 14 times greater than the external dose rate from the weapons grade plutonium. At a contamination depth of 15 cm, the external dose rate from the Du is about 33 times greater than the external dose rate from the weapons grade plutonium. The increasing external dose rate with contamination zone depth illustrates that, even at 15 cm, the soil has not shielded a significant portion of the photon radiation emitted from the DU. The increase in dose rate with depth is because the photon emission from DU emission is of relatively high energy and intensity. About 91 percent of the external dose rate from the depleted uranium is due to U-238 and its decay products. For example, the first four decay products of U-238 emit high energy photons, greater than 500 kiloelectron volts (keV) each, with about 58 percent of the disintegrations. The external dose rate from weapons grade plutonium demonstrates a very different result. The external dose rate increases only slightly after 5 cm. This is due to the relatively low energy and intensity of the photons emitted from the radionuclides comprising weapons grade plutonium and its decay products. About 83 percent of the external dose rate from the weapons grade plutonium is due to Am-241, a decay product from the Pu-241 associated with weapons grade plutonium. Am-241 emits a low energy, 59.5 keV, photon during 35 percent of its disintegrations. This low energy photon is easily absorbed by the soil.

Another significant factor affecting the external radiation dose rate is the bulk density of the soil. The greater the density, the greater the capability of the soil to absorb radiation and shield the dose receptor. The RESRAD code user defines the bulk soil density. Site-specific data will be used for bulk density when it is available; otherwise, a value from another site with the same soil type will be chosen by the code user. A typical value for the bulk soil density on the NTS is 1.5 g/cm^3.

The occupancy rate is the fraction of the time during the year that the hypothetical dose receptor is on the contaminated site. Occupancy rate does not affect external radiation dose rate, but it does affect the external radiation dose received by the dose receptor. Occupancy time is dependent on the living patterns associated with the exposure scenario. The occupancy rate is calculated using two factors. The first factor is the fraction of time spent indoors on site, the second factor is the fraction of time spent outdoors on site. The RESRAD code assumes that the fraction of the time that is not spent indoors and outdoors onsite, is spent off site. The dose receptor does not receive an external exposure when not on site. In calculating guideline concentrations, the total time spent indoors and outdoors while on site is based upon a study of the living patterns of individuals living in rural areas and small communities near the NTS (Henderson and Smale, 1990). The fraction of the time spent on site is also dependent on the area of the site and the exposure scenario being evaluated. For example, a safety shot site on the NTS with an area of 10 hectares (ha) would barely provide the range necessary to pasture a self-sustaining herd of beef and dairy cattle sufficient to supply meat and milk for a family (Stager, 1996). The occupancy rate calculated for a hypothetical rancher on a smaller safety shot site will be reduced proportionally to the area of the site. For example, the occupancy rate for a rancher on a 5-ha site would not exceed 0.25. The time spent on site, and therefore the occupancy rate, is site-and exposure-scenario-specific. A site and exposure specific occupancy rate will be used in calculating guideline concentrations

The fraction of time spent indoors on site is the average fraction of time in a year during which an individual stays inside a house or a building on the contaminated site. This is a dimensionless parameter and is entered in RESRAD as a decimal fraction with a value ranging from 0 to 1. While indoors, the external radiation dose rate is reduced by a user-defined shielding factor. This factor is the ratio of the external gamma dose rate indoors on site to the radiation level outdoors on site and is expressed as a fraction, ranging from 0 to 1. It is based on the fact that a building provides shielding against penetrating gamma radiation. Therefore, the calculation of the effective dose from the ground pathway should take into account this shielding effect. The value used for the shielding factor will be the RESRAD default value of 0.7. This shielding factor assumes that the external gamma radiation level indoors is 30 percent lower than the outdoor gamma radiation level.

The fraction of time spent outdoors on site is the average fraction of time in a year during which an individual stays outdoors on the site. This is a dimensionless parameter and can range from 0 to 1. The fraction of time spent outdoors on-site is exposure-scenario specific and will be calculated for each guideline analysis. The sum of the fraction of time spent indoors on-site, the fraction of time outdoors on site, and the fraction of time spent off-site (not a user input value) should equal 1.

The mathematical expressions that RESRAD uses to calculate ETF_{i1} include the area of the site, thickness of the contamination zone, bulk density of the soil, and the occupancy factors. All of these factors are entered by the RESRAD code user. In addition, RESRAD uses other factors calculated from the user input to calculate ETF_{i1}. These include the area factor, depth factor, and cover factor. The area factor has been discussed previously. The depth factor is a function of the contaminated zone thickness, contamination zone area, and bulk soil density. The depth factor is used in the RESRAD code to correct the external dose rate for the idealized case, infinite depth and area, to the site parameters specified by the code user. Table 4-5 specifies the depth factors for external gamma radiation from contaminated ground as a function of thickness of a contaminated layer exposed at the ground surface and soil density for the principal and associated radionuclides anticipated for the safety shot sites. These are the depth factors used by the RESRAD code. The safety shot sites are not assumed to have any cover, so the cover factor is not pertinent to the calculations of the guidelines. Details regarding the methodology and equations used in calculating ETF_{i1} can be found in Appendix A of the RESRAD User's Manual (Yu et al., 1993a).

4.3 Inhalation Pathway

Inhalation exposures can occur from inhalation of soil resuspended into the air, radon, and radon decay products. The radon exposure pathway is discussed in Section 4.3.6. The inhalation exposure is a function of the average mass loading of the resuspended soil, the annual intake of air by the dose receptor, an area factor, cover and depth factors, and the inhalation dose conversion factor. The first two factors are identified by the RESRAD code user. The next three factors are calculated by RESRAD from user inputs. The dose conversion factors are constants stored in the RESRAD code. This section will discuss these six factors and how they are used in calculating the dose from the inhalation exposure pathway.

Table 4-5

Depth Factors (Fd_{il}) for External Gamma Radiation from Contaminated Ground as a Function of Thickness (t) of a Contaminated Layer Exposed at the Ground Surface and Soil Density (ρ_b) for Principal and Associated Radionuclides at the Safety Shot Sites

	$\rho_b = 1.0\ g/cm^3$			$\rho_b = 1.8\ g/cm^3$		
Radionuclide[a]	**T = 1.5 m**	**T = 0.5 m**	**T = 1.0 m**	**T = 0.15 m**	**T = 0.5 m**	**T = 1.0 m**
Pb-210+D	8.80×10^{-1}	1.0	1.0	9.70×10^{-1}	1.0	1.0
Bi-207	7.39×10^{-1}	1.0	1.0	9.14×10^{-1}	1.0	1.0
Ra-226+D	6.30×10^{-1}	9.20×10^{-1}	1.0	8.50×10^{-1}	1.0	1.0
Ra-228+D	6.80×10^{-1}	9.70×10^{-1}	1.0	8.50×10^{-1}	1.0	1.0
Ac-227+D	7.90×10^{-1}	9.70×10^{-1}	1.0	9.10×10^{-1}	1.0	1.0
Th-228+D	6.10×10^{-1}	9.40×10^{-1}	1.0	7.50×10^{-1}	1.0	1.0
Th-229+D	6.50×10^{-1}	9.50×10^{-1}	1.0	8.50×10^{-1}	9.90×10^{-1}	1.0
Th-230	9.30×10^{-1}	1.0	1.0	1.0	1.0	1.0
Th-232+D	9.50×10^{-1}	1.0	1.0	1.0	1.0	1.0
Pa-231	7.90×10^{-1}	1.0	1.0	9.20×10^{-1}	1.0	1.0
U-232	8.80×10^{-1}	1.0	1.0	1.0	1.0	1.0
U-233	9.60×10^{-1}	1.0	1.0	1.0	1.0	1.0
U-234	9.00×10^{-1}	1.0	1.0	1.0	1.0	1.0
U-235+D	8.70×10^{-1}	1.0	1.0	1.0	1.0	1.0
U-236	9.40×10^{-1}	1.0	1.0	1.0	1.0	1.0
U-238+D	7.80×10^{-1}	1.0	1.0	8.80×10^{-1}	1.0	1.0
Np-237+D	8.20×10^{-1}	1.0	1.0	9.30×10^{-1}	1.0	1.0
Pu-238	9.30×10^{-1}	1.0	1.0	1.0	1.0	1.0
Pu-239	9.20×10^{-1}	1.0	1.0	1.0	1.0	1.0
Pu-240	9.20×10^{-1}	1.0	1.0	1.0	1.0	1.0
Pu241+D	9.01×10^{-1}	1.0	1.0	9.83×10^{-1}	1.0	1.0
Pu-242	9.60×10^{-1}	1.0	1.0	1.0	1.0	1.0
Am-241	9.40×10^{-1}	1.0	1.0	1.0	1.0	1.0

[a]Includes Daughters.

4.3.1 Mass Loading

The mass loading of the resuspended soil is defined as the average annual mass concentration of the soil particles in the air and is measured in grams per cubic meter (g/m^3). The greater the mass loading, the greater the inhalation exposure. Mass loading measurements taken on the NTS and TTR demonstrate wide fluctuations during the year due to freeze and thaw cycles in temperatures during the fall and spring, changes in wind speed, and the effects of precipitation on soil moisture and cohesion. Measurements of mass loading at safety shot sites ranged from 0.77 to 4.1×10^{-5} g/m^3 (Shinn et al., 1986). Mass loadings measured in other rural areas range from 0.9 to 7.9×10^{-5} g/m^3 (Gilbert et al., 1983). In the future, human activities such as plowing and cultivating the soil, vehicular traffic over unpaved areas of the site, and heavy construction activities on the site will increase the mass loading. It is unlikely that there will be sufficient data available to completely characterize the mass loading at every safety shot site.

When site-specific data are not available, data from other safety shot sites with comparable soil types will be used. Mass loading data are available on the mass loading, respirable size fraction, enhancement factor, plutonium resuspension flux rate, resuspension half-time, and the dust concentration, specific activity, and Pu-239 concentration as a function of time during the year for two sites at Area 5. Mass loading measurements have also been taken at Clean Slate 3 (Shinn et al., 1986; Shinn, 1994). These data can be used to calculate an annual average mass loading. However, these mass loading data are descriptive for a site in its present condition.

It is inapplicable to use these mass loadings for activities that may exist during hypothetical future exposure scenarios. The mass loadings must be adjusted to account for human activities and their effect on resuspension of contaminated surface soil. The mass loading for guideline concentration is calculated in the following manner:

$$AML_{k,l} = (1/FO) \times \sum (ML \times Fm_{k,l} \times t_{k,l} \times FC_{k,l}) \qquad (5)$$

where:

AML = adjusted mass loading for exposure scenario k and activity l;

FO = occupancy factor for exposure scenario k, the days per year (d/yr) the hypothetical dose receptor is on the contaminated site; days per year;

ML = average annual mass loading at the Safety Shot site prior to man-made disturbances;

$Fm_{k,l}$ = mass loading enhancement factor, it is the increase in the mass loading for exposure scenario k during activity l (unitless);

$t_{k,l}$ = time period that activity l is occurring for exposure scenario k (d/yr);

$Fc_{k,l}$ = correction factor for the pulmonary deposition for the activity medium aerodynamic diameter of the dust particles being inhaled in comparison to the pulmonary deposition of a 1-micrometer (μm) aerosol using the correction methodology in ICRP 30 (ICRP, 1979-1982) (unitless);

k = index label for the exposure scenario being analyzed, e.g. farming; and

l = index label for the activity in exposure scenario k that is increasing mass loading, e.g. plowing.

The RESRAD default value for mass loading is 2×10^{-4} g/m^3. This value is greater than the largest mass loading reported in rural areas and is at the 95 percentile for mass loadings reported for urban areas, where the mass loading greater (Gilbert et al., 1983). Mass loading will be based upon site-specific data and not the RESRAD default value. The inhalation dose is directly proportional to the mass loading, using data specific to a safety shot sites to calculate the mass loading results in a more representative and defensible inhalation dose. Under-estimating the inhalation dose will produce undesirable biases in estimates of dose.

4.3.1.1 Shielding Factor for the Inhalation Pathway

The RESRAD code allows the user to adjust the mass loading in air during the time periods that the dose receptor is indoors. This factor is defined as the shielding factor for the inhalation pathway. It is the ratio of contaminated airborne dust concentration indoors on site to the concentration outdoors on site. It is based on the fact that a building provides shielding against entry of wind-blown dust particles. Therefore, calculation of the effective dose from the dust inhalation pathway should take into account this shielding effect. This parameter is input as a fraction ranging from 0 to 1. The RESRAD default factor is 0.4, which assumes that the dust level indoors is 40% of the outdoor level (Alzona et al., 1979).

Recent studies have demonstrated that the concentration of respirable dust particles indoors is equivalent to outdoors. Air sampling studies of plutonium aerosols at the NTS have shown that their activity median aerodynamic diameters range from 3 to 5 μm (Layton, 1993). This is the size range observed for crustal elements such as silicon and potassium. Clayton et al. (1993) used personal breathing rate monitors in a study of airborne elements. They found that the concentrations of silicon, potassium, and particulate matter under 10 μm in diameter (i.e., respirable particles) or PM-10 in personal air (obtained from the personal air samplers) were higher than the indoor concentrations measured by stationary samplers indoors. The use of stationary samplers typically show mass loadings are less indoors than outdoors. The personal breathing zone monitor studies demonstrated that the mass loading of respirable particles indoors were equal to the mass loading of respirable particles outdoors. To represent the relationship between the concentrations of plutonium in outdoor air (derived from resuspension of contaminated soil) and personnel exposures indoors, the transfer factor characterizing the movement of plutonium in soil to indoor air is calculated using the methodology in *Cost/Risk Benefit Analysis of Alternative Cleanup Requirements for Plutonium-Contaminated Soils On and Near the Nevada Test Site* (DOE, 1995).

$$TF_{in,s} = (C_{per} / C_a) \times TF_{out,s} \qquad (6)$$

where:

$TF_{in,s}$ = intermediate transfer factor for the movement of Pu in soil to indoor air via soil tracking and air exchange (g/m^3);

C_{per} = personal inhalation exposure to indoor repairable particles (pCi/m^3);

C_a = concentration of suspended particles in outdoor air above a contaminated site (pCi/m^3); and

$Tf_{out,s}$ = intermediate transfer factor for the movement of Pu in soil to outdoor air via resuspension (g/m^3).

Using PM-10 aerosols as a surrogate to represent the movement of plutonium to and within the indoor environment, the geometric mean of the relevant C_{per}/C_a ratios in the study by Clayton et al. (1993) is 1.2, with a geometric standard deviation of 1.8. This supports the hypothesis that the concentration of plutonium in the air indoors is equal to or possibly greater than the concentration of plutonium in the air outdoors. Therefore, the shielding factor for the inhalation pathway in a residence will be set at the maximum value allowed by RESRAD, 1. This value assumes that the mass loading indoors is the same as the mass loading outdoors.

A different inhalation shielding factor must be used for an industrial worker exposure scenario. This is because the shielding factor is used to represent the movement of plutonium into a commercial building. The air-handling systems of such buildings exert positive air pressure indoors; hence, there is no significant infiltration of outdoor air (and associated airborne particles). Instead, outdoor air is continuously introduced to the cooling/heating/ventilation system and exhausted from the building. Layton (1993) calculated a geometric mean transfer coefficient of 5.3×10^{-6} g/m^3, with a geometric standard deviation of 1.56, using Monte Carlo simulations of the input parameters to an indoor-air model (Weschler et al., 1983). The shielding factor would then have a range of 0.07 to 0.55 at two standard deviations. Based upon this transfer coefficient, an inhalation shielding factor of 0.4 will be assumed for the industrial worker exposure scenario. This value is at the 77 percentile of the shielding factor distribution using the data of Weshler et al., (1983). In addition, this shielding factor is also the default value recommended in the RESRAD manual (Yu et al., 1993a) and by the U.S Environmental Protection Agency (EPA) for calculating cleanup of land and facilities contaminated with residual radioactive material (EPA, 1986). This shielding factor will be used for the industrial worker exposure.

4.3.2 Annual Intake of Air

RESRAD requires that the user input the total volume of air inhaled in units of cubic meters per year (m/y). This inhalation rate is calculated by the code user based upon the mixture of activities assumed for the dose receptor. The annual intake of air is calculated on a site-specific basis for each exposure scenario. The annual intake of air is calculated by summing the air intake required for each activity associated with the exposure scenario over all activities assumed to be part of the exposure scenario. The fraction of time spent on site and off site should not affect this input parameter; however, the RESRAD code adjusts the annual intake of air by multiplying it by the occupancy factor. Thus, the calculated annual intake of air will be divided by the occupancy factor to define the input for the RESRAD code. For example, if the calculated annual intake of air for a hypothetical dose receptor is 4,000 cubic meters (m^3) and the occupancy factor is 0.5, the annual intake of air input to RESRAD has to be 8,000 m^3.

Inhalation rate varies with activity level, age, weight, sex, and general physical condition. The activity levels suggested in the RESRAD Data Collection Handbook (Yu et al., 1993b) have been categorized according to criteria developed by the Environmental Criteria and Assessment Office of the EPA for an air quality document on ozone. These categories include resting and light, moderate, and heavy activities. Resting is characterized by such activities as watching television and sleeping. Light activity includes level walking, domestic work and miscellaneous household chores, conducting minor indoor repairs and home improvements, and office work. Moderate activity includes climbing stairs, heavy indoor cleanup, performing major indoor repairs and alterations to the home, and performing light industrial tasks. Heavy activity consists of vigorous physical exercise such as weight lifting, intense sport activities such as riding a bicycle uphill into the wind, and heavy industrial work.

The RESRAD Data Collection Handbook recommendations on activity mixture were adopted for calculating the annual intake of air. For an individual performing outdoor activities, such as the hypothetical rancher, the activity mix consists of the following (Yu et al., 1993b):

- 37 percent at a moderate activity level
- 28 percent at both resting and light activity levels
- 7 percent at a heavy activity level

For an individual performing indoor activities, the reasonable worst-case activity mixture was adopted (Yu et al., 1993b). It includes the following activity mix:

- 25 percent at a resting activity level
- 60 percent at a light activity level
- 10 percent at a moderate activity level
- 5 percent at a heavy activity level

These activity mixtures are used in calculating guidance concentrations.

In order to calculate the annual intake of air, a breathing rate must be defined for each activity assumed in the exposure scenario. Breathing rate is controlled primarily by the amounts of oxygen consumed in the metabolic conversion of food nutrients (i.e., protein, fat, and carbohydrates) to energy. The demand for oxygen and nutrient intakes is a function of our energy expenditures. Important factors influencing both nutrient and oxygen consumption (hence breathing rates), are the age, weight, sex, health status, and activity pattern of the individual. The breathing rates used in calculating guideline concentrations are those computed by Layton (1993). These rates are based upon the oxygen uptake associated with energy expenditures and a ventilatory equivalent that relates minute volume to oxygen uptake. Many of the published breathing rates are inconsistent with the quantities of oxygen needed to metabolize dietary intakes of fats, carbohydrates, and proteins. This inconsistency leads to erroneous estimates of inhalation exposures which can distort the relative importance of inhalation and ingestion-based exposures to the plutonium and uranium isotopes and their decay products that are present in food, air, and water.

The breathing rates found in Layton (1993) which are used in calculating the guideline concentrations use five activities that vary somewhat from those listed in RESRAD. The activity levels are sleep, light activity, moderate activity, hard activity, and very hard activity. The activity level mixes recommended in the RESRAD Data Collection Handbook (Yu et al., 1993b) were adjusted for calculating the guideline concentrations. The adjustments were made based upon the examples in Layton (1993) that were used for each type of activity. The following descriptions demonstrate how the adjustments were made for the reasonable worst-case indoor activity mix from the RESRAD Data Collection Handbook (Yu et al., 1993b) and the data of Layton (1993):

- In RESRAD it was assumed that resting included sleeping, while in Layton these are two separate activities. The indoor worst-case assumes 25 percent of the time, 6 hours per day (h/d), is spent resting. Therefore, this period of time is assumed to be spent sleeping, which is less than the average amount of time spent sleeping by adults, 7.1-7.3 hours per day (Layton, 1993).

- RESRAD assumes 60 percent of the time is spent doing light activities. This percent remains the same using the light activity inhalation rate of Layton (1993).

- In RESRAD it was assumed that 10 percent of the time is spent performing moderate activities. This remains the same for Layton (1993).

- RESRAD assumes that 5 percent of the time is spent doing heavy work. In calculating guidelines, the higher breathing rate associated with the very heavy activity category of Layton (1993) was used.

RESRAD categorizes each inhalation rate by five groups: adult male, adult female, average adult, 6 year old child, and 10 year old child. Layton (1993) organizes the inhalation rates for adults into eight categories, by male and female, and four age groups: 20 to 34 years, 35 to 49 years, 50 to 64 years, and 65 to 74 years. In addition, he also lists daily inhalation rates for five younger age categories: <1, 1- 2 years, 3 to 5 years, 6 to 8 years, and 9-11 year olds. The data cited by Layton (1993) indicated that the daily inhalation rate for 12 to 14 year olds is only 12 percent less than that for adults. For calculating the guidance concentration, the data for 20 to 34 year olds was used. This choice may be conservative by a factor of 10-15 percent. However, this amount of conservatism is very small in comparison to the variation in other factors used in calculating dose to individuals. For calculating the annual intake of air by a child dose receptor the weighted average breathing rates of Layton (1993) for children <1 to 11 years old were assumed.

4.3.3 Area Factor

The area factor represents the fraction of airborne dust that is contaminated. For on-site exposure, the transport process may be regarded as a dilution process in which the resuspended contaminated dust is mixed with uncontaminated dust blown in from off site. This dilution can be modeled by a Gaussian plume model using an area distribution of point sources with a zero release height or by a simple mixing model that assumes perfect mixing of resuspended on-site contaminated dust with off-site uncontaminated dust within a volume defined by a mixing height and the area of the contaminated zone. There are very large uncertainties regarding the use of the Gaussian plume model for an on-site exposure; it is not generally considered applicable over distances of less than 100 m. RESRAD incorporates a simple mixing model in calculating the area factor.

It is calculated by using a mixing model for estimating the dilution of contaminated dust that is resuspended on site by uncontaminated dust blown in from offsite and is given by the formula:

$$FA_2 = (A)^{1/2}/[(A)^{1/2} + DL] \qquad (7)$$

where:

A = area of contaminant zone (m^2); and
DL = dilution length (m).

The dilution length (DL) depends on the wind speed, mixing height, resuspension rate, and thickness of the resuspendable soil layer (Gilbert et al., 1983, Appendix A). Estimates of the lower and upper bounds of DL for bounding values of the independent variables are 0.03 m and 250 m, respectively. The geometric mean of the bounds, DL = 3 m, is used as the default value in RESRAD and is the value assumed for calculating guideline concentrations. The safety shot sites are sufficiently large (>15 ha) that assuming a DL value of three will result in less than a 3 percent reduction in the concentration of the resuspended soil contaminant, in comparison to its concentration in the soil.

4.3.4 Cover and Depth Factor

The cover and depth factor is the fraction of resuspendable soil particles at the ground surface that are contaminated. It is a derived value calculated by RESRAD from the following measured data that is inputted by the RESRAD code user: depth of the soil mixing layer (m), cover depth at time t (m), and thickness of the contaminated zone at time t (m). RESRAD calculates the cover and depth factor $FCD_2(t)$ using the following formula:

$$
\begin{aligned}
FCD_2(t) &= 1 && \text{when} \quad C_d(t) = 0,\ T(t) \geq d_m \\
&= T(t)/d_m && \text{when} \quad C_d(t) + T(t) < d_m \\
&= 1 - C_d(t) && \text{when} \quad C_d(t) < d_m,\ C_d(t) + T(t) \geq d_m \\
&= 0 && \text{when} \quad C_d(t) \geq d_m
\end{aligned}
\tag{8}
$$

where:

d_m	=	depth of soil mixing layer (m);
$C_d(t)$	=	cover depth at time t (m); and
$T(t)$	=	thickness of contaminated zone at time t (m).

Additional details on the cover and depth factor can be found in the RESRAD User's Manual (Yu et al., 1993a).

4.3.5 Inhalation Dose Conversion Factor

The inhalation dose conversion factor, DCF_{i2}, is a multiplicative factor that converts the intake of radionuclide to a committed effective dose equivalent. The DCF_{i2} is radionuclide-specific, is defined for dust particles with an activity median aerodynamic diameter of 1 µm, and assumed lung clearance rates. The rate of clearance from the lung is based upon which of three inhalation classes is assigned to the radionuclide. The three inhalation classes are D, W, and Y which correspond to retention half-times in the lung of less than 10 days, 10 to 100 days, and greater than 100 days, respectively. Some radionuclides are assigned to two or three inhalation classes. The inhalation class of the radionuclide is dependent on its chemical form. The DCF_{i2} values for the principal radionuclides to be encountered on the safety shot sites are listed in Table 4-6. These DCF_{i2} values will be used in calculating guideline concentrations. The DCF_{i2} values listed in Table 4-6 are the RESRAD code default values and are the most conservative DCF_{i2} recommended by the EPA (Eckerman et al., 1988). Less conservative DCF_{i2} will be used if, and only if, analysis of resuspended contaminated soil demonstrates that a less conservative value is appropriate.

Table 4-6
Dose Conversion Factors for Inhalation
(mrem/pCi)

Isotope	Dose Conversion Factor for Inhalation
Ac-227+D[a]	6.720E+00
Am-241	4.440E-01
Np-237+D	5.400E-01
Pa-231	1.280E+00
Pb-210+D	2.320E-02
Pu-238	3.920E-01
Pu-239	4.290E-01
Pu-240	4.290E-01
Pu-241+D	8.250E-03
Pu-242	4.110E-01
Ra-226+D	8.600E-03
Ra-228+D	5.080E-03
Th-228+D	3.450E-01
Th-229+D	2.160E+00
Th-230	3.260E-01
Th-232	1.640E+00
U-233	1.350E-01
U-234	1.320E-01
U-235+D	1.230E-01
U-236	1.250E-01
U-238+D	1.180E-01

[a]Ac-227+D means that the dose conversion factor is for Ac-227 plus all its decay products with a half-life of less than six months.

The DCF_{i2} for uranium isotopes is based upon their chemical toxicity. The risk from an intake of uranium is dominated by its effect as a heavy metal and the damage done to the functions of the kidney, liver, and spleen.

Adjustments may be made to the DCF_{i2} due to particle size distributions that are significantly different than 1 μm. The exposure scenarios analyzed in calculating guideline concentrations result in mixtures of particle size distributions. The particles size distribution that differ from the default value of 1 μm are corrected using equation (5). If the particle size distribution correction is made instead to the DCF_{i2}, the methodology used to adjust the DCF_{i2} is that discussed in ICRP Publication 26, Section 5.5 (ICRP, 1977a). For example, the particle size distribution of resuspended particles measured at safety shots in Plutonium Valley and GMX had a geometric mean of 5.5 to 5.7 AMAD had a geometric standard deviation of 7.9 (Shinn, 1986). The DCF_{i2} for these particles is about 10 percent of the value for a 1 μm AMAD particle size distribution with a GSD of 2.0 (ICRP, 1978). The adjustment to the DCF_{i2} depends on the distribution of the particle size around the mean. A geometric standard deviation of two is recommended by the ICRP (ICRP, 1979-1982). The formula for adjusting the DCF_{i2} is shown below:

$$DCF_{i2}\,(AMAD) = \{[f_{N\text{-}P} \times D_{N\text{-}P}\,(AMAD)/D_{N\text{-}P}\,(1\ \mu m)] + [f_{T\text{-}B} \times D_{T\text{-}B}\,(AMAD)/D_{T\text{-}B}\,(1\ \mu m)] + [f_P \times D_P\,(AMAD)/D_P\,(1\ \mu m)]\} \times DCF_{i2}\,(1\ \mu m) \quad (9)$$

where:

DCF_{i2} (AMAD) = DCF_{i2} for the site-specific particle size distribution (mrem/pCi);

$f_{N\text{-}P}$ = fraction of the committed effective dose equivalent from the particles deposited in the nasal passage;

$D_{N\text{-}P}$ (AMAD) = deposition probability of the site-specific particles size distribution in the nasal passage;

$D_{N\text{-}P}$ (1 μm) = deposition probability for a 1 μm (AMAD) particle size distribution;

$f_{T\text{-}B}$ = fraction of the committed effective dose equivalent from the particles deposited in the trachea and bronchial tree;

$D_{T\text{-}B}$ (AMAD) = deposition probability of the site-specific particle size distribution in the trachea and bronchial tree;

$D_{T\text{-}B}$ (1 μm) = deposition probability for a 1 μm (AMAD) particle size distribution in the trachea and bronchial tree;

f_P = fraction of the committed effective dose equivalent from the particles deposited in the pulmonary parenchyma;

D_P (AMAD) = deposition probability of the site-specific particle size distribution in the pulmonary parenchyma;

D_P (1 µm) = deposition probability for a 1 µm (AMAD) particle size distribution in the pulmonary parenchyma; and

DCF_{i2} (1 µm) = dose conversion factor from inhalation for a 1 µm (AMAD) distribution.

The values for the deposition probabilities in the respiratory regions, the nasal-pulmonary, trachea and bronchial tree, and the pulmonary parenchyma, are from Figure 5-1 of ICRP Publication 30 (ICRP, 1979-1982). The fraction of the committed effective dose equivalent in the reference tissue resulting from deposition in the nasal-pulmonary, trachea and bronchial tree, and the pulmonary parenchyma must be calculated. These fractions are radionuclide-specific, and they require solving 19 interlinked, first-order differential equations. The specifics about how that is performed are described in Section 5 and the Appendix of ICRP Publication 30 (ICRP, 1979-1982).

Details regarding how the RESRAD code uses the parameter values supplied by the user and the derived values calculated internally by the code for the inhalation pathway are described in detail in Appendix B of the RESRAD User's Manual (Yu et al., 1993a).

4.3.6 Radon Inhalation Pathway

Radon is a radioactive noble gas that will diffuse from the soil and be inhaled. Radon migrates continuously through the soil from radium present in the soil. This is known as radon exhalation. When inhaled, a portion of the radon and its progeny will decay, resulting in irradiation of the lung tissue closest to the air passages. The radon that is breathed into the lungs is mostly breathed out before decay. The hazard from radon arises from its decay progeny, which are not gaseous; when they are breathed in, they deposit on the interior surface of the lung.

The radionuclides associated with the safety shot sites that decay to radon include U-234, U-235, and U-238 in addition to Pu-238, Pu-239, Pu-240, and Pu-242. All of these radionuclides decay to a radium isotope which then decays to radon. However, the inhalation of radon and its decay products is not expected to be a dominant dose contributor of radiation exposure. The build-up of radium from these radionuclides is very slow. The rate of radium (Ra-226) ingrowth through the decay of Pu-242, Pu-238, U-238, and U-234 is controlled by the 4.468 billion year half-life of U-238 and the 445,00 year half-life of U-234. The Ra-226 build-up will be negligible. The exhalation of radon (Rn)-222 from the decay of Ra-226 will be insignificant. The ingrowth of Ra-223 from Pu-239 and U-235 decay is controlled by the U-235 half-life of 70.38 million years. There will be negligible build-up of Ra-223, which decays to Rn-219. Rn-219 has a half-life of less than 4 seconds and will not migrate far from where it is produced. The ingrowth of Ra-224 from the decay of Pu-240 is controlled by the 14.05 billion year half-life of Th-232. Negligible build-up of Ra-224 is expected. The Rn-220 exhalation from the soil will be insignificant. Preliminary results from RESRAD calculations using standard default values and extraordinarily large source terms, 1,000 pCi/g of DU uniformly distributed through a depth of 15 cm, results in a radon dose of approximately 0.1 mrem/yr in the year of the maximum radon dose.

Calculation of the effective dose equivalents (EDEs) from airborne radon and radon decay products requires an estimate of the following:

- The radon exhalation from the ground surface
- The radon concentration in the air that results from this flux
- The airborne concentration of radon decay products associated with this concentration

A generalized radon pathway model is included in RESRAD for estimating the amount of radon released, its concentrations in both indoor and outdoor air, and the resulting radiation dose as a function of time from the initial time of consideration. The effects of cover materials, geological parameters, wind speed and precipitation, decay and ingrowth, and leaching and erosion are considered with respect to near-term radon releases and long-term releases extending for thousands of years. All time-dependent parameters that would affect the radon release rate are considered by the radon pathway model. The indoor air concentration is calculated by a model in which radon enters the room through the floor and through ventilation inflow from the outdoor air. The radon concentration is diluted with the air in the room. In addition, the radon concentration is reduced by radioactive decay and ventilation. Radon contamination of groundwater is included in the RESRAD radon model for completeness.

4.3.6.1 Radon Exhalation

This section discusses how radon migrates from the ground, concentrates in the outdoor and indoor air, the decay and ingrowth of radon and its progeny, and radon dose methodology. The discussion will emphasize the sources and methodologies for calculating user input parameter values. The RESRAD User's Manual should be consulted for additional detail regarding the radon exposure pathway model (Yu et al., 1993a).

Radon decay products are chemically active and attach to soil particles. Consequently, they do not move significantly in the ground. Radon exhalation may be caused by convection or diffusion. The factors that affect the exhalation of the radon gas include: size distribution and configuration of the soil and building pore spaces, moisture content of the soil, windspeed, atmospheric pressure, ground cover such as snow, and temperature. All of these factors are highly time-dependent and practically unpredictable. Consequently, the rate of radon exhalation to the outdoor environment and infiltration into indoor air usually varies with time and cannot be readily quantified.

The rate of radon generation into the soil pore volume is calculated by RESRAD using the user-input radon emanation coefficient, the bulk soil density, the code-calculated radium concentration in soil, and the radon decay constant that is stored in the code. Assuming a horizontally infinite and homogeneous soil and neglecting the convective flow of the soil gas in the porous matrix of the soil, the radon flux is calculated by RESRAD using the Fickian diffusion equation. Subsequently, the radon concentration and flux along the direction through the soil and any building on the soil is calculated using a one-dimensional radon diffusion equation. Site-specific data are used for the pore space volume and bulk soil density. Default values are used for all other factors. Details on the methodology for calculating radon exhalation from soils can be found in the RESRAD User's Manual (Yu et al., 1993a).

4.3.6.2 Radon Concentration Outdoors and Indoors

The radon concentration in the outdoor air above a contaminated site is influenced by the radon flux from the ground surface, environmental factors, atmospheric stability, and time. The average radon concentration outdoors on top of a contaminated area would most likely be dependent on the size of the contaminated area and the average wind speed and would not be very sensitive to other meteorological parameters. The concentration outdoors would be relatively small compared to that indoors. The mathematical expression used by the RESRAD code to compute the annual average concentration of radon outdoors (pCi/m^3) is a complex function of the following factors:

- Radon flux at the soil surface outdoors ($pCi/s\text{-}m^2$)
- Height into which the plume is uniformly mixed (2 m)
- Outdoor area factor (dimensionless)

- Area of the contaminant zone (m^2)
- Annual average wind speed (meters per second [m/s])

Site-specific data required to calculate these factors are the area of the contamination and the annual average wind speed. The method for calculating the contaminated site area was previously discussed in Section 4.2.2. The annual average wind speed will be obtained from either a local meteorological station or the appropriate site-specific annual environmental report. All other parameter values required to calculate the outdoor radon concentration are derived by RESRAD. Details can be found in the RESRAD User's Manual (Yu et al., 1993a).

Indoor radon levels depend on many parameters including building characteristics and meteorological conditions. Radon enters a building by exhalation from the ground through the foundation floor and below-grade walls, by the inflow of outdoor air brought in by ventilation, and by the use of water where dissolved radon will out-gas. RESRAD assumes a steady-state, one-compartment model to determine the radon concentration indoors. The model requires the following parameter data:

- Radon flux from the floor built on the contaminated site (pCi/s-m^2)
- Interior surface area of the house floor (m^2)
- Indoor area factor (dimensionless)
- Interior volume of the hours (cubic meters)
- Decay constant of radon (decay/s)
- Ventilation rate of the house (house volumes ventilated[s])

The user-defined parameter values required by RESRAD to solve the indoor radon concentration include the thickness, density total porosity, volumetric water content, and effective radon diffusion coefficients of the building foundation. RESRAD default values are chosen for these parameters. Other user-defined parameters include: the contaminated zone radon diffusion coefficient, radon vertical dimension of mixing, average annual wind speed, the building air exchange rate, room height, and indoor area factor, and the radon emanation coefficients for Rn-222 and Rn-220. Site-specific data are chosen for the annual average wind speed, and RESRAD default values are used for all other parameters.

4.3.6.3 Indoor Radon Concentration in Air from Water Use

Groundwater containing radium can add to the amount of radon in the air indoors. Radon is partitioned between air and water in an approximate ratio of 4 to 1, respectively, at 20 degrees centigrade in the environment under equilibrium conditions (Nazaroff et al., 1988). When water is used, for example in the shower, dissolved radon can escape. Various studies (Mueller Associates, Inc., 1986; Bodansky et al., 1987) on correlating the radon concentration in the air of typical homes with the concentrations in water supplies have indicated that the ratios are on the order of 10^{-4}. This value implies that water containing 10,000 picoCuries per liter (pCi/L) of radon would typically increase the indoor radon concentration by 1 pCi/L. Due to the very insignificant concentration of radium expected in the safety shot site soils, the dose from this exposure pathway is not expected to exceed zero. Preliminary calculations of the water use exposure pathway for radon, even for a very conservative source term of 1,000 picoCuries per gram of depleted uranium in soil uniformly distributed in a 15-cm thick contaminated zone, resulted in doses $<10^{-14}$ mrem/yr.

4.3.7 Radon Dose Calculation

In RESRAD, the radiation dose from radon and its progeny is calculated by using the accumulated exposure in terms of working level month (WLM). The WLM is a cumulative exposure unit historically applied to uranium miners and is now defined as the combination of the short-lived radon progeny in 1 liter (L) of air that results in the ultimate release of 1.3×10^5 megaelectron volts (MeV) of potential alpha energy times the duration of exposure, normalized to a 170-hour working month exposure (ICRP, 1981, 1986). In RESRAD, the application of WLM to the general population follows the approach of a proportional factor, K, which was first introduced qualitatively in the BEIR IV report (NRC, 1988) and later analyzed quantitatively by a companion study to BEIR IV (NRC, 1991).

Because the environmental conditions in a mine and the physiological characteristics of miners are, respectively, significantly different from those for a home or members of the general public, the dose conversion factors derived for miners have to be revised. The methodology used in RESRAD is based on the K factor introduced in the BEIR IV report. The K factor is a dimensionless proportionality factor that converts the risk or dose to the lung in miners per WLM to the risk or dose to an individual in a home per WLM. No RESRAD user inputs are used to calculate the conversion of radon and its decay progeny to WLM or to dose. Constants stored in the RESRAD code are used to calculate the dose due to the inhalation of radon and its decay progeny. Details on the RESRAD methodology can be found in Appendix C of the RESRAD User's Manual (Yu et al., 1993a).

4.4 *Ingestion Pathways for Plants, Meat, Milk, and Drinking Water*

Ingestion pathways consist of five environmental pathways and the common exposure pathway to which they contribute (see Table 4-1). The doses from these pathways are specified by the dose/source ratios that were described previously in Section 4.1.3. A dose/source ratio may be defined as the sum of the product of the dose conversion factor (which characterizes the exposure pathway), the environmental transport factor (which characterizes the environmental pathways), and the source factor (which characterizes ingrowth and decay and leaching of the radionuclides).

The dose conversion factor for ingestion is the ratio of the committed effective dose equivalent incurred by an individual from intake by ingestion of a quantity of a radionuclide and is expressed in millirems per picoCuries (mrem/pCi). Values of DCFs for ingestion are stored in RESRAD and are taken from an EPA report (Eckerman et al., 1988). The DCFs for ingestion are tabulated in Table 4-7. Dose conversion factors are a function of the chemical form of the radionuclide, which determines the fraction of a radionuclide entering the gastrointestinal tract that reaches the blood stream and can, thus, be transported to the various tissues and organs. The RESRAD default vales are the most conservative DCF value recommended in the EPA report (Eckerman et al., 1988) and are the DCFs assumed in calculating the guideline concentrations.

The DCFs for ingestion of uranium isotopes is based upon their chemical toxicity. The risk from an intake of uranium is dominated by its effect as a heavy metal and the damage done to the functions of the kidney, liver, and spleen.

The environmental transport factors for the plant, meat, and milk pathways are calculated using area factors, cover and depth factors, the food/soil concentration ratios, and the annual consumption of the foods in the six food classes defined by RESRAD; fruits, grains, leafy vegetables, non-leafy vegetables, meat, and milk. The area, cover, and depth factors have been defined and discussed previously for the inhalation pathway in Section 4.3. The annual consumption of the different food classes is input by the RESRAD code user. The consumption rate of all food items assumed in calculating the guideline concentrations is based upon a 10-county, lifestyle survey relevant to rural areas and towns of less than 25,000 residents in the arid and semi-arid Western United States in Southern Nevada, Southern Utah, and Northern Arizona (Whicker et al., 1990). The consumption rate is also dependent on the site area and exposure scenario. Therefore, the consumption rate has to be calculated on a site-specific basis for each exposure scenario. The consumption rate for the food stuffs is area-dependent: if the

Table 4-7
Dose Conversion Factors for Ingestion
(mrem/pCi)[a]

Isotope	Dose Conversion Factor for Ingestion
Ac-227+D[b]	1.480E-02
Am-241	3.640E-03
Np-237+D	4.440E-03
Pa-231	1.060E-02
Pb-210+D	7.270E-03
Pu-238	3.200E-03
Pu-239	3.540E-03
Pu-240	3.540E-03
Pu-241+D	6.850E-05
Pu-242	3.360E-03
Ra-226+D	1.330E-03
Ra-228+D	1.440E-03
Th-228+D	8.080E-04
Th-229+D	4.030E-03
Th-230	5.480E-04
Th-232	2.730E-03
U-233	2.890E-04
U-234	2.830E-04
U-235+D	2.670E-04
U-236	2.690E-04
U-238+D	2.690E-04

[a]Millirems per picoCurie
[b]Ac-227+D means that the dose conversion factor is for Ac-227 plus all its decay products with a half-life of less than six months.

area is not sufficient to grow the crops to feed the a family, the amount of contaminated food consumed is decreased linearly.

The consumption rate of fodder and water by beef cattle assumed for the guideline calculations is in accordance with the values listed in NRC Regulatory Guide 1.109 (NRC, 1977), while the consumption rate for dairy cattle is that published by Gilbert et al. (1983). The soil ingestion rate of livestock is from a study performed for the Idaho National Engineering Laboratory (Rope and Adams, 1983). Data on the area required to raise livestock were obtained from the Forestry Division and the Department of Conservation and Natural Resources of the State of Nevada.

Resuspended soil can be deposited on plant leaves, be absorbed by the plant, and be directly deposited on the edible parts of the plant. This is known as foliar deposition. RESRAD calculates the foliar deposition and resulting ingestion intake as a function of the cover and depth factors, plant-food/air concentration ratios, and air/soil concentration ratios. The ratios are element-dependent and stored in the RESRAD code. The transfer factors for meat and milk uptake via the root pathway are listed in Table 4-8. The vegetable/soil transfer factors for root uptake are listed in Table 4-9. These are the transfer factors used in calculating the guideline concentrations.

The drinking water pathway allows the RESRAD code user to define the volume of water consumed by individuals and livestock and the fraction of the water that is obtained from an on-site well. The rate of water consumption by livestock (liters per day [L/d]) was chosen to correspond to the national averages (Gilbert et al., 1983). Beverage and fluid consumption by individuals has been studied numerous times. The values vary from 0.2 to 2.2 L/d. Studies that distinguished tap water intake from intake of other fluids (e.g., milk, soft drinks, alcohol, and fruit juices) demonstrate a medium tap water ingestion rate of 0.957 L/d (Roseberry and Burmaster, 1992). The RESRAD Data Collection Handbook recommends a drinking water intake of 1.4 L/d (Yu et al., 1993b). This drinking water ingestion rate corresponds to the 80th percentile of the tap water ingestion rate studied by Roseberry and Burmaster (1992). This is the drinking water ingestion rate assumed in calculating guideline concentrations.

The drinking water is assumed to be obtained from a well located at the downgradient edge of the remediated area. This location will ensure that the water from the well will receive the maximum amount of contamination from the soil.

Table 4-8
Food Transfer Factors for Meat (pCi/kg)[a]/(pCi/d)[b] and Milk (pCi/L)/pCi/d) Intakes

Isotope	Meat	Milk
Ac-227+D[c]	2.00E-05	2.00E-05
Th-228+D	1.00E-04	5.00E-06
Th-229+D	1.00E-04	5.00E-06
Th-230	1.00E-04	5.00E-06
Th-232	1.00E-04	5.00E-06
U-233	3.40E-04	6.00E-04
U-234	3.40.E-04	6.00E-04
U-235+D	3.40E-04	6.00E-04
U-236	3.40E-04	6.00E-04
U-238+D	3.40E-04	6.00E-04
Am-241	5.00E-05	2.00E-06
Np-237+D	1.00E-03	5.00E-06
Pa-231	5.00E-03	5.00E-06
Pb-210+D	8.00E-04	3.00E-04
Pu-238	1.00E-04	1.00E-06
Pu-239	1.00E-04	1.00E-06
Pu-240	1.00E-04	1.00E-06
Pu-241+D	1.00E-04	1.00E-06
Pu-242	1.00E-04	1.00E-06
Ra-226+D	1.00E-03	1.00E-03
Ra-228+D	1.00E-03	1.00E-03

[a] pCi/kg - PicoCurie(s) per kilogram
[b] pCi/d - PicoCurie(s) per day
[c] Ac-227+D means that the dose conversion factor is for Ac-227 plus all its decay products with a half-life of less than six months.

Table 4-9
Food Transfer Factors for Soil to Plants
(dimensionless)

Isotope	Food Transfer Factor
Ac-227+D[a]	2.50E-03
Th-229+D	1.00E-03
Th-230	1.00E-03
Th-232	1.00E-03
U-233	2.50E-03
U-234	2.50E-03
U-235	2.50E-03
U-236	2.50E-03
U-238+D	2.50E-03
Np-237+D	2.00E-02
Pa-231	1.00E-02
Pb-210+D	100E-02
Pu-238	1.00E-03
Pu-239	1.00E-03
Pu-240	1.00E-03
Pu-241+D	1.00E-03
Pu-242	1.00E-03
Ra-226+D	4.00E-02
Ra-228+D	4.00E-02
Th-228+D	1.00E-03
Am-241	1.00E-03

[a]Ac-227+D means that the dose conversion factor is for Ac-227 plus all its decay products with a half-life of less than six months.

4.5 Soil Ingestion Pathway

Soil and dust derived from soil are accidentally ingested by individuals, both while outdoors and indoors. According to guidance by the U.S. Environmental Protection Agency (EPA, 1989), soil ingestion should be considered separately for adults and children for residential scenarios. The input value for the soil ingestion rate, in grams per year, depends strongly on the assumed scenario. The soil intake rates assumed in calculating guideline concentrations are based upon the pilot study by Calabrese et al. (1990). This study has been adopted by the EPA and the American Industrial Health Council (AIHC) (EPA, 1991; AIHC, 1994). The methodology used in applying the Calabrese et al. (1990) study is as follows:

- While on site, an individual engaged in agricultural activities (i.e., plowing or rototilling) will be assumed to be ingesting soil at a rate of 0.48 grams per day (g/d).
- While working on site in an industrial position, an individual is assumed to be ingesting soil at a rate of 50 milligrams per day (mg/d).
- Other on-site residents are assumed to be ingesting soil at a rate of 100 mg/d while engaging in garden or other outdoor activities; otherwise, their soil ingestion rate is 50 mg/d.
- When not on site, individuals are not ingesting contaminated soil.

The RESRAD code uses a series of equations to calculate the dose/source ratio, dose conversion factors, environmental transport factors, and source factors for calculating the dose from the ingestion of soil. The parameters supplied by the code user to RESRAD are the soil ingestion rate (g/year), the area of the contaminated site, the mixing depth of the soil, thickness of the contaminated zone, and the fraction of time the individual is on site. All of these factors have been discussed previously. Detailed discussions of the models and equations used by the RESRAD code in calculating dose from soil ingestion can be found in Appendix F of the RESRAD User's Manual (Yu et al., 1993a).

4.6 Groundwater Pathway

The groundwater pathway describes the transport of the radionuclides from the soil, through the vadose zone to the saturated zone, and flow in the saturated zone to a well where it is withdrawn for drinking or for irrigation. This pathway is characterized using a water/soil concentration ratio for each radionuclide. This ratio is defined as the ratio of the radionuclide concentration in the water at the point of withdrawal or use to the radionuclide concentration in the contaminated zone. Calculations of the guidance concentration assume that the well is always at the downgradient edge of the contaminated zone. The parameters used to analyze the groundwater pathway include the breakthrough time, rise time, and dilution factor. The breakthrough time is the time from a radionuclide's release into infiltrating water at the contaminate zone until its detection at the point of withdrawal or use. The rise time is the time from initial detection until the concentration reaches a maximum value. The dilution factor is the steady-state ratio of a radionuclide concentration at the point of withdrawal or use to the concentration of the same radionuclide in infiltrating water as it leaves the contaminated zone. The RESRAD code assumes the hydrological strata can be approximated by a sequence of uniform, horizontal strata.

The parameter values supplied by the RESRAD code user for the groundwater pathway are discussed in the following text:

- RESRAD default values are assumed for the runoff coefficient and well pump intake depth.
- No cover is assumed to be on the remediated soil at the safety shot site.
- Site-specific data are used to calculate all other groundwater parameters using the methods described in the RESRAD User's Manual, (Yu et al., 1993a).

The site-specific data required as RESRAD input for the groundwater pathway include:

- Site specific data used to determine the contaminated zone erosion rate and the water table drop rate
- Density, total porosity, effective porosity, thickness, and hydraulic conductivity for the contaminated zone, vadose zone, and saturated zone; the absolute humidity in the air, and precipitation
- Evapotranspiration, *b* parameter, irrigation rate, and watershed area for nearby streams or ponds, all of which have to be calculated by the user based upon site-specific data
- Distribution coefficients for each radionuclide in each of the contaminated, unsaturated, and saturated zones based on site-specific measurements or referenced data for the type of strata

The contaminated zone erosion rate is the average volume of soil material that is removed from the contaminated zone by running water or wind. The contaminated zone erosion rate represents the average depth of soil that is removed from the ground surface per unit of time at the safety shot site and is expressed in units of meters per year. When available, site-specific monitoring data will be used for the contaminated zone erosion rate. If site-specific data is not available, the RESRAD default value of 0.001 meter per year (m/yr) will be adopted for calculating guideline concentrations (Yu et al., 1993b).

The water table drop rate is the rate, in units of meters per year, at which the depth of the water table is lowered. The level of the water table in a groundwater system fluctuates seasonally because of the erratically temporal variation of the processes involved in the hydrological cycle as well as the variation in demand made by human water supply and use systems. The site-specific water table drop rate can be estimated from a local monitoring station appropriately installed in the vicinity of the site. If there is no monitoring well the water table drop rate used in calculating guideline concentrations will estimated by consulting water table records.

Density is the ratio of the mass of the soil to the volume. For heterogeneous and multiphasic materials such as soils, care will be taken to ensure that the density is measured using a sufficiently large volume of soil containing a large number of pores so that the concept of mean global properties is applicable, and yet of a sufficiently small volume so that the variations of any parameter of the soil from one part of the domain to another can be approximated by continuous functions. In the RESRAD code, the density is assigned to represent the dry density, measured in units of g/cm^3, for each of the following four materials:

- Contaminated zone
- Unsaturated zone
- Saturated zone
- Building foundation material

Site-specific density data will be used for calculating guideline concentrations. If site-specific density data are not available, a density of 1.5 g/cm^3 will be used for the soil in the first three zones and 2.4 g/cm^3 will be used for the building foundation (Yu et al., 1993b).

The total porosity of a soil system is the ratio of the pore volume to the total volume in the soil system. Total porosity is a dimensionless quantity and is entered in the RESRAD code as a decimal fraction. The RESRAD code user is required to enter total porosity for four materials:

- Contaminated zone
- Unsaturated zone
- Saturated zone
- Building foundation material such as concrete

When available, site-specific data on the total porosity will be used in calculating guideline concentrations. If site-specific data are not available, the total porosity appropriate to the safety site will be chosen from a value listed in Table 3.2 of the RESRAD Data Collection Handbook, based upon the soil type (Yu et al., 1993b).

The effective porosity is defined as the ratio of the part of the soil pore volume where the water can circulate to the total volume of a representative sample of the medium. In the RESRAD code, the effective porosity values are entered as decimal fractions. To use RESRAD in calculating guideline concentrations, the code user is required to input effective porosity values for three distinct zones:

- Contaminated zone
- Unsaturated zone
- Saturated zone

In surface soils, where the flow of water is caused by the composition of capillary, molecular, and gravitational forces, the effective porosity can be approximated by the specific yield, or drainage porosity, which is defined as the ratio of the volume of water drained by gravity from a saturated representative sample of the soil to the total volume of the sample. If available, site-specific values of the effective porosity will be used in calculating the guideline concentrations. If site-specific data are not available, the effective porosity values will be chosen from Table 3.2 of the RESRAD Data Collection Manual, based upon the soil type at the safety shot site (Yu et al., 1993b).

The thickness is the distance between the uppermost and lowermost layers of the contaminated zone, the unsaturated zone, and the saturated zone. In the RESRAD code, the thickness is measured in meters. Site-specific, *in situ* measurements will be used in determining the thickness of the contamination zone. Thickness of the unsaturated and saturated zones will be defined based upon monitoring wells or water tables maps of the vicinity of the safety shot site.

Hydraulic conductivity is a measure of the soil's ability to transmit water when submitted to a hydraulic gradient. Hydraulic conductivity is defined by Darcy's law, which, for one-dimensional vertical flow, can be written as follows:

$$U = -K\, dh/dz \qquad (10)$$

where:

U = the average velocity of the soil fluid through a geometric cross-sectional area within the soil;

h = the hydraulic head;

z = the vertical distance in the soil over which U is measured; and

K = the hydraulic conductivity (m/y).

The hydraulic conductivity depends on the soil grain size, the relative amount of saturation present in the soil matrix, soil pore size distribution, shape, tortuosity, specific surface of the soil, and soil porosity, and the water viscosity and density. In the RESRAD code, the user is requested to input a saturated hydraulic conductivity value for three soil zones: contaminated, unsaturated, and saturated zones. For calculating guideline concentrations, site-specific geological stratigraphy and soil textures will be used to estimate the hydraulic conductivity using Table 5.5 in the RESRAD Data Collection Handbook (Yu et al., 1993b).

The absolute humidity is the mass of water vapor in the air per unit volume and is measured in units of g/m^3. The annual average absolute humidity assumed in calculating guideline concentrations will be calculated using measured temperature and relative humidity at the safety shot site. If site-specific temperature and relative humidity measurements are not available, then the absolute humidity will be estimated using the data in the annual environmental report for the safety shot site.

The precipitation assumed for calculating the guideline concentrations at a safety shot sites will be the annual average rainfall reported in the annual environmental reports for the safety shot site area.

The evapotranspiration coefficient represents the total volume of water that changes phase (i.e., from the liquid or solid state to the gaseous state) near the ground surface and is then transferred to the atmosphere. It can also be thought of as the ratio of the total volume of water leaving the ground as a result of evapotranspiration to the total volume of water available within the root zone of the soil during a fixed period of time. The evapotranspiration coefficient is calculated using equation 12.1 in the RESRAD Data Collection Handbook (Yu et al., 1993b). The evapotranspiration coefficient is site-specific and is calculated as a function of the precipitation rate, the irrigation rate, the runoff coefficient, and the evapotranspiration rate. The evapotranspiration rate is the total volume of water vapor that is transferred to the atmosphere because of the combined effect of evaporation and transpiration, per unit of the ground surface area and per unit of time at the site. In accordance with the guidance in the RESRAD Data Collection Handbook, the potential evapotranspiration rate (displayed in Figure 12.1 of the Handbook) is substituted for the evapotranspiration rate (Yu et al., 1993b).

Thickness is the distance between the uppermost and lowermost levels in the contaminated, unsaturated, and saturated zones. In the RESRAD code, thickness of the zones is measured in meters (m). Site-specific data derived from *in situ* gamma spectroscopy measurements will be used to define the contaminated zone thickness. The thickness of the other zones will be based upon site-specific data. If site-specific data is not available, then water table maps of the vicinity of the safety shot site will be used to define the zone thickness.

The soil-specific exponential *b* parameter is one of several hydrological parameter values used to calculate the radionuclide leaching rate of the contaminated zone. The soil-specific exponential *b* parameter is an empirical and dimensionless parameter that is used to evaluate the saturation ratio or the volumetric water saturation of the soil, according to a soil characteristic function called the conductivity function. It is a site-specific parameter and is calculated using equation 13.4 in the RESRAD Data Collection Handbook (Yu et al., 1993b). It is calculated by the user as a function of the saturated and unsaturated hydraulic conductivity.

The irrigation rate is the amount of water, measured in m/y, required to grow crops on the contaminated sites. It is calculated by subtracting the precipitation rate from 2 m/y and dividing by the irrigation efficiency. The site-specific precipitation rate will be obtained from annual environmental reports. The irrigation efficiency assumed is 0.7.

The watershed area is defined as a region contoured by an imaginary line connecting ridges or summits of high land and drained by or draining into a river, river system, or a body of water such as a lake or pond. It is the surface area of the draining region above the discharge measuring points. In RESRAD, it represents the area of the region draining into the nearby stream or pond located at the vicinity of the site. In order to be conservative, the watershed area is assumed to be equal to the contaminated zone area of the site.

The distribution coefficient is the ratio of the mass of solute species adsorbed or precipitated on the solids per unit of dry mass of the soil to the solute concentration in the liquids. In calculating guideline concentrations, the distribution coefficients assumed are those for sandy soil listed in Table 32.1 of the RESRAD Data Collection Handbook (Yu et al., 1993b).

Preliminary analysis of the safety shot sites at Double Track and Clean Slate I, using site-specific data, demonstrates that the groundwater pathway contributes a negligible dose. All water pathways have contributed less than 10^{-9} mrem/yr, even for a conservative source term of 1,000 pCi/g of depleted uranium or weapons grade plutonium uniformly distributed throughout the top 15 cm of soil. The low dose from the groundwater pathway is due to the extraordinary low concentrations of contaminates reaching the groundwater. The thickness of the vadose zone and the high value for the evapotranspiration rate ensures that virtually no radionuclides reach the groundwater from contaminated surface soil.

5.0 Exposure Scenarios

The Department of Energy does not define a standard set of exposure scenarios for calculating guideline concentrations. The guidance provided in DOE Order 5400.5 (DOE, 1993) is to use "worst-case" or "plausible-use" scenarios, use specific property data where available, and remain consistent with the procedures and guidance provided in DOE/CH-8901 (Gilbert et al., 1989). A review of guideline concentrations for 19 DOE uranium-contaminated soil sites has been published; each site adopted a different set of exposure scenarios in calculating the guideline concentrations (Kamboj et al., 1996).

Various types of land uses could eventually emerge at the NTS, TTR, and NAFR if active institutional controls were lost. An important requirement for any future development in this arid environment is the availability of groundwater. The existing geohydrological data for this region of Nevada indicate that there is probably enough groundwater to support some development. However, no estimates are available to determine whether the aquifer yields are great enough to continuously sustain widespread development at the various safety shot sites.

There are other obvious land-use constraints on commercial development at the safety shot sites: no paved or all season unpaved roads, no groundwater wells, no power lines, no services typically supplied by county, city, or utility services, and long distances from sources of raw materials. In addition to these constraints, there are additional constraints to agricultural development: poor soil, a harsh climate, and rough terrain. Nevertheless, three basic land uses that could potentially occur in the future were identified: agricultural worker, rural resident, and industrial worker. Each land use has an associated exposure scenario that consist of a series of assumptions and parameters defining how an individual comes in contact with the radioactive source terms present on the contaminated soil. The following sections provide qualitative descriptions of the three basic land uses and the parameters and data used to estimate the applicable exposure pathway exposure factors.

5.1 Agricultural Scenarios

Land use that involves agriculture is assumed to center around a farm or ranch house that is located on contaminated soil. An important human factor determining the magnitude of human exposures in this type of scenario is the amount of time spent outdoors on site on the contaminated land. This is defined as the occupancy factor in RESRAD. In calculating guideline concentrations, the area comprising the agricultural operations is assumed to be limited to the contaminated area. If large commercial ranching or farming operations were assumed, a significant portion of the worker's time would not be spent on the contaminated land. In addition, large operations would result in crops and livestock being raised on uncontaminated soil.

Calculating the guideline concentration assuming large agricultural operations would be nonconservative, resulting in a reduced and biased dose as a function of the concentration of the radiological source term in the soil. In this regard, limiting agricultural activities to the contaminated area would involve the hypothetical dose receptor being required to spend a significant amount of time on the contaminated land. The safety shot sites are large enough to support a self-sustaining herd of beef or dairy cows or raise the fruits, vegetables, and grains to feed a family. Calculation of the guideline concentration for the agricultural scenarios assumes small family ranches or farms exist on the safety shot site. Lifestyle data for the agricultural scenarios is based upon the articles in a special issue of the Health Physics Journal, *Evaluation of Environmental Radiation Exposures from Nuclear Testing in Nevada* (Gesell and Voilleque, 1990).

Two agricultural exposure scenarios were assumed: a resident rancher and a resident farmer. The guideline concentrations are calculated separately for each of these two exposure scenarios. This is because the activities used in each are significantly different. For example, due to the low annual precipitation rate a farmer would have to irrigate the land. The irrigation water leaches the radiological source term from the surface, diluting the concentration of the radiological source term by distributing it through a deeper layer of the soil, and thereby reduces the dose received by the farmer. The farmer is assumed to plow, disk, and till the soil. These activities will mix the radionuclides on the surface soil with the uncontaminated soil below the surface, diluting the concentration of the radiological source term, and thereby reduce the dose to the farmer. At the same time, the activities involved in farming (such as plowing, disking, and tilling) will increase the mass loading of radiological contaminated soil into the air, increase the radionuclide intake to the farmer via the inhalation pathway, and thereby increase the dose to the farmer. The rancher is assumed to pasture his herds and not perform activities that would dilute the concentration of the radiological source term (such as plowing, disking, and tilling). A detailed description of the activities associated with each of the agricultural exposure scenarios follows.

5.1.1 Rancher Scenario

The hypothetical rancher is a plausible, but very unlikely, scenario. At the safety shot sites, the precipitation rates are low, the production of palatable herbs, grasses, and other forage for cattle is very low, and there is a minimum of infrastructure available to support even a subsistence rancher. Selection of the ranching exposure scenario and exposure pathways will result in conservative (i.e. stringent) dose estimates for a future hypothetical dose receptor. However, in order to ensure that a full set of exposure scenarios are evaluated, the rancher exposure scenario is used in calculating guideline concentrations.

Under the rancher exposure scenario, a total of seven exposure pathways are evaluated:

- External radiation exposure from photon-emitting radionuclides in soil
- Inhalation of resuspended soil and dust containing radionuclides
- Inhalation of radon gas
- Incidental ingestion of soil and dust containing radionuclides
- Ingestion of contaminated drinking water
- Ingestion of meat containing radionuclides taken up by cows raised on site
- Ingestion of milk containing radionuclides taken up by cows raised on site

The parameter values used in the rancher scenario are those listed in Table 5-1 and are derived, to the extent possible, from surveys taken on the lifestyles of families living in rural areas and small communities in a 10-county area around the NTS (Henderson and Smale, 1990; Whicker et al., 1990).

The rancher is assumed to raise beef cattle and dairy cows full-time on the contaminated safety shot site and to reside on the site 24-hours per day, 337 days per year (Adams, 1996). The rancher spends 15 hours per day outside on site and 9 hours per day indoors.

While on site, the rancher is breathing air assumed to have an average mass loading greater than the baseline mass loading for the site. The baseline mass loading is the mass loading measured at the site or in the vicinity of the site prior to human habitation. Equation 5 will be used to adjust the mass loading upward using the specific activities associated with ranching. If specific ranching activities are not identified, the mass loading for the rancher is assumed to be twice the baseline mass loading for the site. This value was chosen because some short-lived ranch activities are expected to increase the mass loading in the air while most ranching activities may,

Table 5-1
Parameter Values for the Rancher Exposure Scenario

Parameter (Units)	Numerical Value
Exposure Frequency (d/yr)	337
Inhalation Rate (m^3/d)[a]	8010
Soil Ingestion Rate (mg/d)	131
Exposure Time Indoors On Site (h/d)	9
Exposure Time Outdoors On Site (h/d)	15
Shielding Factor for Inhalation	1
Drinking Water Ingestion Rate (L/d)	1.86
Leafy Vegetable Ingestion Rate (g/d)	29.5[a]
Non-leafy Vegetable, Fruit, and Grain Ingestion Rate (g/d)	354[a]
Milk Ingestion Rate (L/d)	0.61
Beef and Poultry Ingestion Rate (g/d)	274

[a]Obtained from a farm with soil contamination equivalent to his ranch.

at most, result in negligible increases in the mass of dust in the air (Shinn et al., 1986). If site specific data is not available, an adjusted mass loading of 4.4E-5 g/m^3 will be assumed. This is the mean value for the range of mass loadings measured in rural areas (Gilbert et al., 1983). This mass loading is approximately 3.2 times higher than the annual average baseline mass loading measured at Clean Slate 3 safety shot site (Shinn, 1994).

The assumed inhalation rate of the rancher is based upon that for a typical outdoor activity (Yu, et al., 1993b). He is assumed to sleep seven hours per day. During his waking hours, he is assumed to spend 28 percent of the time at both resting and light activity level, 37 percent at a moderate activity level, and 7 percent at a heavy activity level, which results in an annual inhalation rate of 8,100 m^3/year (Yu et al., 1993a; Layton, 1993).

While outdoors, the rancher is exposed to an external radiation rate that is 3.33 times that of indoors. Water is obtained from a well located at the downgradient edge of the contaminated site. This location of the well ensures that the water from the well receives the maximum amount of contamination from the soil. All drinking and household water is obtained from this well. The rancher is assumed to drink 1.4 L of tap water per day, 472 L per year (AIHC, 1994).

The rancher is assumed to raise half of his own meat, milk, and their by-products from cattle and cows raised on the contaminated site. In addition, he obtains half of his annual food consumption of fruits, vegetables, and grains from a farm whose soil contamination is equivalent to his ranch. The consumption rate of all food items is based upon a 10-county, lifestyle survey relevant to rural areas and towns of less than 25,000 residents in the vicinity of the NTS (Whicker et al., 1990).

All livestock is raised on site, and their only source of drinking water is the on-site well. The beef cattle and dairy cows are assumed to ingest 50 kg of fodder per day. The beef cattle are assumed to ingest 50 L of water per day, while the dairy cattle ingest 160 L of water per day (NRC, 1977; Great Lakes Basin Commission, 1975). In addition, both the cattle and cows are assumed to ingest 0.5 kg of contaminated soil per day (Rope and Adams, 1987).

The radon inhalation dose to the rancher is maximized by assuming the residential building foundation depth is set on the soil surface and the effective radon diffusion coefficient is 3×10^{-7} square meters per second (m^2/s) (Yu et al., 1993a).

5.1.2 Farmer Scenario

The hypothetical farmer is a plausible, but very unlikely, scenario. As stated previously, the precipitation and the soil productivity at the safety shot sites is very low, irrigation and fertilization will be required to raise crops. The depth to groundwater varies from 80 to several hundred meters on the safety shot sites; the cost of groundwater wells may make agricultural prohibitive. In addition, there is negligible infrastructure available to support farming. However, in order to evaluate a full set of exposure scenarios the farming scenario is included. The selection of the farming scenario will result in conservative dose estimates for future hypothetical residents on the safety shot sites.

Farming activities in southern Nevada were assumed to be indicative of future farming on the safety shot sites and will include alfalfa farms and orchards. These agricultural uses are more likely to result in outdoor exposure to airborne contaminants adjacent to a farmhouse as the irrigated land is assumed to be in the direct vicinity of the farmer's residence. Thus, in this exposure scenario an individual would spend a considerable amount of time outdoors farming, with the remainder of time indoors in barns, outbuildings, or the farmhouse; all of which are assumed to be on contaminated soil.

Under the farming scenario, a total of seven exposure pathways are evaluated:

- External radiation exposure from photon-emitting radionuclides in soil
- Inhalation of resuspended soil and dust containing radionuclides
- Inhalation of radon gas
- Incidental ingestion of soil and dust containing radionuclides
- Ingestion of contaminated drinking water
- Ingestion of contaminated, home-grown produce (fruits, vegetables, and grains)

The parameter values used for the farmer scenario are those listed in Table 5-2 and are derived, to the extent possible, from surveys taken of residents living in rural and small communities in a 10-county area in the vicinity of the NTS (Henderson and Smale, 1990; Whicker et al., 1990).

Table 5-2
Parameter Values Used in the Farming Exposure Scenario

Parameter (Units)	Values
Exposure Frequency (d/yr)	337
Inhalation Rate (m^3/d)	8010
Soil Ingestion Rate (mg/d)	131
Exposure Time Indoors (h/d)	9
Exposure Time Outdoors (h/d)	15
Shielding Factor for Inhalation	1
Drinking Water Ingestion Rate (L/d)	1.86
Leafy Vegetable Ingestion Rate (g/d)	29.5
Non-leafy Vegetable, Fruit, and Grain Ingestion Rate (g/d)	354
Milk Ingestion Rate (L/d)	0.61[a]
Beef and Poultry Ingestion Rate[a] (g/d)	274[a]

[a]Obtained from a ranch with soil contamination equivalent to his farm.

While on site, the farmer is breathing air assumed to have an average mass loading greater than the baseline mass loading for the site. Equation 5 will be used to adjust the baseline mass loading upward assuming specific activities associated with farming. These activities will be based upon rural Nevada lifestyle surveys when available; otherwise information on farming activities derived from the open scientific literature will be assumed. If no baseline mass loading is available, a value of 4.4E-5 g/m^3 will be assumed. This is the mean value for the range of mass loadings measured in rural areas (Gilbert et al., 1983). This mass loading is approximately 3.2 times higher than the annual mean mass loading measured at the Clean Slate 3 safety shot site (Shinn, 1994).

If no specific farming activities have been identified, an adjusted mass loading of 8.8E-5 g/m^3 will be assumed. The annual inhalation rate assumed for the farmer is the same for the rancher, 8,010 cubic meters (m^3). While outdoors, the farmer is exposed to an external radiation rate that is 3.33 times that indoors.

The farmer is assumed to obtain all of his household and irrigation water from a well located at the downgradient edge of the contaminated site. This location of the well ensures that the water from the well receives the maximum amount of contamination from the soil. All drinking and household water is obtained from this well. The farmer is assumed to drink 1.4 L of tap water per day, 472 L per year (AIHC, 1994).

The farmer is assumed to raise half of all the vegetables, fruits, and grains consumed during the year. The consumption rate is based upon a 10-county, lifestyle survey relevant to rural areas and towns of less than 25,000 residents in the vicinity of the NTS (Whicker et al., 1990).

The radon inhalation dose to the farmer is maximized by assuming the residential building foundation depth is set on the soil surface and the effective radon diffusion coefficient is 3×10^{-7} square meters per second (m^2/s) (Yu et al., 1993a).

In the agricultural exposure scenarios, a sharp distinction was made between the activities of the rancher and the farmer. In reality, this may not always be the case. For example, the rancher may raise food crops for his own consumption. The farmer may raise poultry, rabbits, beef cattle, or dairy cows as a source of meat and milk. To ensure that the dose calculated for the rancher and farmer is conservative and bounding, the following assumptions were made:

- The rancher obtains half of his annual food consumption of fruits, grains, and vegetables from a farm whose soil has the same concentration and type of radiological contamination as his ranch.

- The farmer obtains half of his annual food consumption of meat, milk, and their by-products from a ranch whose soil has the same concentration and type of radiological contamination as his farm.

5.2 Rural Resident Scenario

The rural residential exposure scenario is assumed for calculating guideline concentrations and addresses the dose to a hypothetical rural resident expected to live on a safety shot site subsequent to remediation. The rural resident scenario is a plausible, but unlikely, scenario. Primarily for the same reasons, the agricultural exposure scenarios are unlikely; the harsh climate and minimal infrastructure will not encourage residency on the safety shot sites. However, this exposure scenario was chosen because it is a current standardized exposure scenario used by the EPA's Superfund program and in their proposed rule for cleanup of radiologically contaminated soil (EPA, 1993; EPA, 1994).

Under the rural resident scenario, individuals are assumed to live on site and be exposed chronically, both indoors and outdoors, to residual concentrations of radionuclides in soil. The rural resident scenario is based primarily on EPA's standardized residential scenario and exposure pathways used in their proposed soil cleanup rule for radiological contaminated soils, NTS specific values are used for the variable input parameters (EPA, 1993; EPA, 1994).

The hypothetical future resident is assumed to work primarily off site and engage only in light gardening and recreational activities on site. Furthermore, it is assumed that 50 percent of the locally grown produce, meat, and milk that these individuals consume are assumed to come from the site and are contaminated.

Under the residential scenario, a total of eight exposure pathways are evaluated:

- External radiation exposure from photon-emitting radionuclides in soil
- Inhalation of resuspended soil and dust containing radionuclides
- Inhalation of radon gas
- Incidental ingestion of soil and dust containing radionuclides

- Ingestion of contaminated drinking water
- Ingestion of contaminated home-grown produce (fruits, vegetables, and grains)
- Ingestion of meat containing radionuclides taken up by cows raised on site
- Ingestion of milk containing radionuclides taken up by cows raised on site

Selection of this scenario and combination of exposure pathways will result in relatively conservative doses to a rural resident from the residual contamination at the safety shot sites subsequent to remediation.

The parameter values used for the resident scenario are those listed in Table 5-3 and are derived from the EPA proposed rule for cleanup of radiological contaminated soil (EPA, 1993).

Table 5-3
Parameter Values for the Rural Resident Exposure Scenario

Parameter	Numerical Value
Exposure Frequency (d/yr)	337
Inhalation Rate (m^3/d)	20
Soil Ingestion Rate (mg/d)	100
Exposure Time Indoors (h/d)	14.9
Exposure Time Outdoors (h/d)	0.4
Shielding Factor for Inhalation	0.4
Drinking Water Ingestion Rate (L/d)	1.4
Leafy Vegetable Ingestion Rate (g/d)	29.5
Non-Leafy Vegetable Ingestion Rate (g/d)	154
Fruit Ingestion Rate (g/d)	122
Grain Ingestion Rate (g/d)	78
Milk Ingestion Rate (L/d)	0.61
Beef and Poultry Ingestion Rate (g/d)	274

The exposure frequency is based upon studies of rural residents living in the vicinity of the NTS (Henderson and Smale, 1990). The produce, meat, and milk ingestion rate are from studies on the food consumption rates estimated from a 10-county life-style survey data taken of rural residents living in the vicinity of the NTS (Whicker et al., 1990). The inhalation rate is calculated from the breathing rates published by Layton (1993) using the activity mixture for a reasonable worst-case for individuals performing indoor activities (Yu et al., 1993b). This case is defined for an individual spending 8 hours per day sleeping, and during the remaining day 25 percent at a resting activity level, 60 percent at a light activity level, 10 percent at a moderate activity level, and 5 percent at a heavy activity level (Yu et al., 1993a). The drinking water ingestion rate is the recommended rate by the American Industrial Health Council for use in risk assessment (AIHC, 1994).

All other exposure parameter values listed in Table 5-1 for the resident scenario are those recommended by the EPA in their proposed rule for cleanup of residual radioactive soil contamination (EPA, 1993; 1994). Site-specific data will be used for all other parameter values required by the RESRAD code for calculating guideline concentrations.

The resident is assumed to spend 0.4 hours per day performing outdoor activities associated with maintaining his garden, orchard, cattle, chickens, and rabbits (EPA, 1993). During these activities, the concentration of contaminated dust in the air is assumed to increase by a factor of 150 (Shinn et al., 1986). While outside, the resident is exposed to an external radiation rate that is 3.33 times greater than when in doors. The resident is assumed to inadvertently ingest 100 milligrams (mg) of contaminated dirt per day (Calabrese et al., 1990). The radon inhalation dose is maximized by assuming the residential building foundation depth is set on the surface and the effective radon diffusion coefficient is 3×10^{-7} m^2/s (Yu et al., 1993a).

5.3 *Industrial Scenario*

The industrial worker is assumed to be engaged in commercial activities such as solar energy research or light manufacturing, processing, or fabrication. The industrial worker scenario is plausible, but very unlikely. The safety shot sites are not located where industrial infrastructure such as power and telephone lines, water, all-season roads, and raw materials is available.

The parameter values assumed for the industrial exposure scenario that were used to calculate guideline concentrations are identical to those defined by the EPA for Superfund cleanups and in the proposed rule for cleanup of radiologically contaminated soil (EPA, 1993; EPA, 1994). The exceptions are the breathing rates and inadvertent soil ingestion rates; they were obtained from Yu et al. (1993b), and Layton (1993).

This scenario addresses long-term exposures and risks to commercial or industrial workers exposed daily to residual levels of radionuclides in soil during an average 8-hour workday on site, both indoors and outdoors. This scenario does not consider exposures to site remediation workers or construction workers, nor does it address risks to workers from contaminated structures or building materials.

Under the industrial exposure scenario, a total of five pathways are evaluated:

- External radiation exposure from photon-emitting radionuclides in soil
- Inhalation of resuspended soil and dust-containing radionuclides
- Inhalation of radon
- Incidental ingestion of soil containing radionuclides
- Ingestion of drinking water containing radionuclides transported from soil to groundwater

The dose to the industrial worker will generally be less than those for residents of rural areas because worker exposures are limited to working hours and do not include contributions from ingestion of home-grown produce. As a result, doses for workers are expected to be consistently lower than those for individuals assuming residential or agricultural exposure scenarios. The parameter values assumed for the industrial worker exposure scenario are listed in Table 5-4.

Table 5-4
Parameter Values for the Industrial Worker Exposure Scenario

Parameter	Numerical Value
Exposure Frequency (d/yr)	250
Inhalation Rate (m^3/d)	12.6
Soil Ingestion Rate (mg/d)	50
Exposure Time Indoors (h/d)	8
Exposure Time Outdoors (h/d)	2
Inhalation Shielding Factor	0.4
Drinking Water Ingestion Rate (L/d)	0.875

The inhalation rate is calculated using the following activity mixture: 60 percent of their time is spent performing light work, 30 percent of their time is spent performing moderate work, and 10 percent of their time is spent performing very heavy work. The breathing rates assumed are from Layton (1993).

A drinking water ingestion rate was not identified by the EPA in their industrial worker exposure scenario. In calculating guideline concentrations, it is assumed that the industrial worker ingest 62.5 percent (10 h/d at work out of 16 h/d they are awake) of his daily ingestion rate of 1.4 L/d while at work (Roseberry and Burmaster, 1992).

5.4 *Child Dose Receptor*

The child dose receptor is evaluated to determine the difference, if any, between the dose received by a child in comparison to an adult. It will be used as a subset of the agricultural and resident scenarios. The child dose receptor is not pertinent to the industrial worker exposure scenario.

The child dose receptor describes the living patterns, breathing rates, and diet for children up to age eleven. The parameter values that describe the child dose receptor are listed in Table 5-5. To the extent possible, the parameter values assumed are derived from lifestyle surveys taken in rural areas and small communities in the vicinity of the NTS (Henderson and Smale., 1990).

Table 5-5
Parameter Input Values for the Child Scenario

Parameter (Units)	Numerical Value
Exposure Frequency (d/yr)	330
Inhalation Rate (m^3/d)	12.3
Soil Ingestion Rate (mg/d)	24
Exposure Time Indoors (h/d)	18.4
Exposure Time Outdoors (h/d)	5.6
Shielding Factor for Indoor Inhalation	0.4
Drinking Water Ingestion Rate (L/d)	0.32
Leafy Vegetable Ingestion Rate (g/d)	18.5
Non-leafy Vegetable, Fruit, and Grain Ingestion Rate (g/d)	397
Milk Ingestion Rate (L/d)	1.18
Meat and Egg Ingestion Rate (g/d)	153

The exposure frequency, exposure time indoors, and exposure time outdoors for elementary school children (ages 5 to 11 years old) were derived from Figure 2 of Henderson and Smale (1990). For children ages 3 and 4, data was obtained from the EPA Exposure Factors Handout; the AIHC Exposure Factors Sourcebook (EPA, 1989; AIHC, 1994). Very young children, less than three years old, were assumed to spend one-half as much time off site and outdoors on site as children six to eleven years old, based upon the site-specific data of Henderson and Smale (1990).

The soil ingestion rate assumed for children is based upon the quantifiable soil ingestion rates obtained in the studies of Calabrese and Stanek (1991). The median soil ingestion value for children was reported as 16 mg/d with a 97.5 percentile of 24 mg/d. The 24 mg/d value was assumed for the child exposure scenario.

The inhalation rate assumed for the child dose receptor is a weighted average value derived from the daily inhalation rates for children of less than one to eleven years of age, listed in Table 5 of Layton (1993).

The drinking water ingestion Rate assumed for the child dose receptor is a weighted average taken from Table 5.9, *Average and Range of Daily Intake of Tap Water and Beverages Other than Milk for Various Age Groups*, Report No. 76 of the National Council on Radiation Protection and Measurements (NCRP, 1985).

The ingestion rate of fruits, leafy and non-leafy vegetables, grains, meat and poultry, and milk assumed for the child dose receptor is derived from Table 5-3, "Best Estimates of Average Daily Intake of Various Foods by Age" in NCRP Report No. 76 (NCRP, 1985).

The mass loading, indoor shielding factor for inhalation, dilution length for airborne dust, and the indoor shielding factor for external radiation for the child dose receptor is assumed to be the same as for adults.

6.0 Conclusions

Residual plutonium, uranium, and their radioactive decay products exist in surface soil at the safety shot sites. Remediation of the safety shot sites requires that guideline concentrations be calculated for the residual radioactive contamination. The methodology for calculating guideline concentrations for the safety shot sites has been presented. Emphasis has been placed on describing the exposure pathway modeling and procedures recommended in the RESRAD code user's manual and data collection handbook (Yu et al., 1993a,b). This code is prescribed in DOE Order 5400.5 as the methodology to be applied for calculating guideline concentrations. All exposure pathways pertinent to the safety shot sites were discussed. Examples are presented for those pathways that are considered to be the most significant.

Four exposure scenarios were developed to evaluate radiation doses to hypothetical future dose receptors. The exposure scenarios include: two agricultural scenarios (ranching and farming), a rural resident, and an industrial worker. A child dose receptor was also developed for use with the agricultural and rural resident exposure scenarios. These exposure scenarios were selected because they address plausible, though very unlikely, uses to which the safety shot sites could be applied, if institutional control is released. In addition, the exposure scenarios developed are conservative, they should bound the dose received by any hypothetical future dose receptor.

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