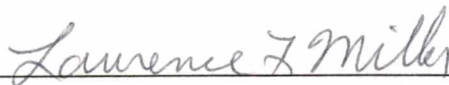


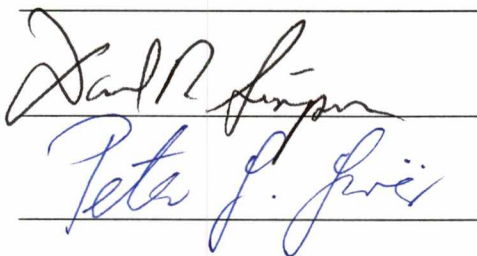
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Date November 30, 1993

**A RADIOLOGICAL ASSESSMENT OF THE 903 PAD, MOUND, EAST TRENCHES
AND OFF-SITE AREAS AT THE ROCKY FLATS PLANT**

**A Thesis
Presented for the
Master of Science Degree
The University of Tennessee, Knoxville**

**Bryan S. Johnson
December 1993**

DEDICATION

To my parents, James and Delores, and my
friends, Danae, Jeff, and Larry

ACKNOWLEDGEMENTS

The author extends his sincerest appreciation to a number of individuals for their assistance and support during the course of this assessment. In particular, the author is indebted to Martin Marietta Energy Systems, Inc., the Hazardous Waste Remedial Actions Program (HAZWRAP), the United States Department of Energy, EG&G Rocky Flats, and the following individuals: Hal Davidson, Tom Brennan, Tom Ham, Bob Magee, and Ron Rhea.

The author wishes to thank Professors Larry F. Miller, Peter Groer, and David Simpson, who served as director and committee respectively, for their helpful comments on this work. I would also like to thank Professor Tom McGehee for helping me to understand the geology and hydrology at Rocky Flats.

Thanks are also due to Argonne National Laboratory and the United States Department of Energy for the use of the RESRAD code and to Dr. Charley Yu and Lynn Jones for their assistance and guidance.

This research was sponsored by the Environmental Restoration and Waste Management Organization of the Hazardous Waste Remedial Actions Program (HAZWRAP) which is managed by Martin Marietta Energy Systems, Inc. for the United States Department of Energy under contract DE-AC05-84OR21400.

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A RADIOLOGICAL ASSESSMENT OF THE 903 PAD, MOUND, EAST TRENCHES, AND OFF-SITE AREAS AT THE ROCKY FLATS PLANT

Bryan S. Johnson

ABSTRACT

This thesis presents a radiological assessment of three contaminated areas at the Rocky Flats Plant in Colorado. The first area is located in Operable Unit 2 (OU 2) in the southeastern portion of the plant. The other two areas are located just off-site to the east. The goal of this thesis is to determine whether the U.S. Department of Energy (DOE) can release these areas to the public or whether it must remediate them, based on the requirements and procedures outlined in DOE Order 5400.5, "Radiation Protection of the Public and Environment."

The methodology used to perform the assessment is based on DOE/CH/8901, "A Manual for Implementing Residual Radioactive Material Guidelines, A Supplement to U.S. Department of Energy Guidelines for Residual Radioactive Material at Formerly Utilized Sites Remedial Action Program and Surplus Facilities Management Program Sites." The calculations were made using Argonne National Laboratory's RESRAD computer model (Version 4.6) that uses the methodology in DOE/CH/8901.

The critical pathways for radiation exposure are principally dust inhalation and soil ingestion. When the distribution coefficients are low, drinking-water ingestion can be also be a more serious exposure pathway, as can water-dependent plant and meat ingestion. The dose comes principally from Am-241.

Under worst-case conditions, the dose to a receptor in the northern and southern off-site areas is under the base radiological dose limit (BRDL) of 100 mrem/yr. Thus, both of these areas may be released to the public. Under average (nominal) conditions at

the on-site area, the dose to a receptor is 60 mrem/yr, which is under the limit. However, increasing the soil mass loading to its maximum value or reducing the distribution coefficient to its minimum value raises the dose above the limit. Under worst-case conditions, the dose is 3760 mrem/yr. Thus, the on-site area may require remediation. The single radionuclide guideline for Am-241 is about 7.1 picocuries per gram (pCi/g) for low distribution coefficients and 0.83 pCi/g for the worst-case scenario. Reducing the soil concentrations of Am-241 below the guidelines reduces the dose below the limit for the respective conditions. More study is necessary.

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1. INTRODUCTION

1.1 HISTORY OF THE ROCKY FLATS PLANT

The nuclear weapons complex of manufacturing and research facilities was established during World War II under the Manhattan Project, and it continued to expand in the 1950s with the development of thermonuclear fission in the United States and the development of nuclear weapon technology in the Soviet Union. The complex's mission was to produce nuclear material; conceive, design, test, develop, refine, and manufacture nuclear weapons; and dispose of all obsolete weapons.

Necessary for the maintenance of the nuclear weapons complex was a new facility to manufacture, at a full-scale production level, nuclear weapon components. The Atomic Energy Commission (AEC) decided that building a new facility near an existing city would be an economically-sound decision, and after investigating various sites, it chose a location 16 miles northwest of Denver, Colorado, to build the Rocky Flats Plant (RFP). Figure 1.1 illustrates this location.

Construction began in 1952 and limited operations began the following year. AEC awarded the first contract to Dow Chemical Company to operate the plant. In 1975, the AEC was dissolved, and the Energy Research and Development Administration (ERDA) was created. In the same year, the Atomics International Division of Rockwell International replaced Dow Chemical Company. Within 2 years, ERDA was dissolved and replaced by the U.S. Department of Energy (DOE). DOE and Rockwell International operated RFP until 1990, when the contract with Rockwell International was not renewed. EG&G Rocky Flats has been in charge of operations since then.

RFP fabricated nuclear weapon components from plutonium, uranium, beryllium, and stainless steel. These components were shipped to other facilities for final assembly.

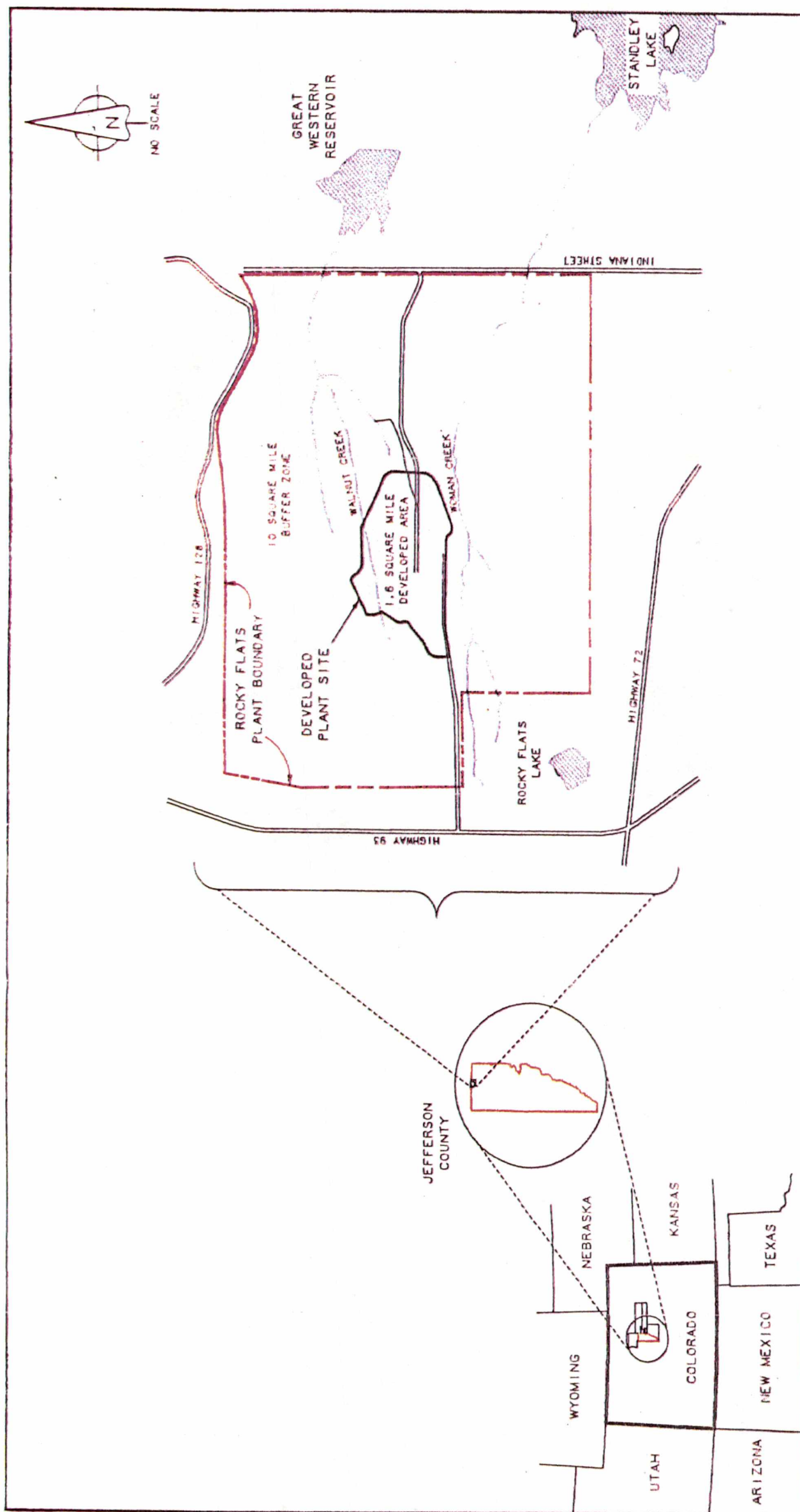


Figure 1.1. Location of the Rocky Flats Plant

Source: "Draft Rocky Flats Plant Surface Water Management Plan," EG&G Rocky Flats, Inc., March 1991.

Support activities included chemical recovery of plutonium; component retirement operations; vehicle modifications for nuclear weapons transportation; and research and development in metallurgy, machining, nondestructive testing, coatings, remote engineering, chemistry, and physics (EG&G, 1992a; EG&G, 1991b).

Over the past four decades, production and waste management operations at RFP have significantly contaminated the environment with hazardous and radioactive contaminants. The plant's soil, sediments, groundwater, and surface water are contaminated with volatile organic compounds (VOCs), inorganic compounds, metals, and other hazardous contaminants. Radionuclides are present in the plant's soil, sediments, and surface water. They, however, have not been conclusively identified in the ground water. The primary radionuclide contaminants are plutonium (Pu) and americium (Am) (Congress, 1991; EG&G, 1991b).

In June of 1989, the United States Department of Justice (DOJ), the Environmental Protection Agency (EPA), and the United States Federal Bureau of Investigation (FBI) executed a search warrant of the plant with the Secretary of Energy's and DOE Inspector General's assistance. This warrant was part of an ongoing investigation into environmental regulation infractions by Rockwell International, the management and operating (M&O) contractor for RFP. In November DOE halted plutonium-related production activities at RFP. Production activities have since been altered to that of decontamination and decommissioning (D&D) for the following reasons.

On September 27, 1991, President Bush announced the cancellation of several nuclear weapons programs that significantly diminished RFP future production requirements. The Secretary of Energy, Admiral James Watkins, later decided to accelerate consolidation of non-nuclear manufacturing facilities.

On January 28, 1992, in his State of the Union Address, President Bush announced the cancellation of further production of the Trident II missile and the W-88 nuclear warhead. The mission of RFP is changing from one of nuclear weapons production to one of cleanup, deactivation, and preparation for decontamination and decommissioning.

On February 10, 1992, the Secretary of Energy submitted a report to Congress from the DOE regarding the RFP. Various new missions were defined, including (1) clean-out and stabilization of production process systems, (2) decontamination of obsolete and/or excess buildings and facilities, (3) processing of plutonium residues in preparation for transport to storage/disposal sites, (4) possible transferring of non-plutonium manufacturing to other locations, (5) maintaining a contingency status in Building 707 pending final decisions from the reconfiguration Programmatic Environmental Impact Statement (PEIS), and (6) providing technical assistance in developing the design of a replacement facility to be evaluated in the PEIS (EG&G, 1992a).

1.2 REGULATIONS CONCERNING THE CLEANUP OF THE ROCKY FLATS PLANT

Cleanup activities at DOE facilities are regulated by the Resource Conservation and Recovery Act (RCRA); the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA); state and local requirements; and internal DOE Orders, standards, and guidance documents. The principal DOE Order overseeing cleanup for the RFP is DOE Order 5400.5, "Radiation Protection of the Public and the Environment."

DOE Order 5400.5 establishes standards and requirements for effluent discharges and residual radioactive material. RCRA regulates the treatment, storage, and disposal of hazardous wastes or radioactive waste mixed with hazardous pollutants. CERCLA provides for liability, compensation, cleanup, and emergency response for hazardous substances released into the environment and for the cleanup of inactive hazardous waste disposal sites.

In addition, the Colorado Department of Health (CDH) has proposed a special plutonium soil guideline of 0.9 picocuries per gram (pCi/g) in soil. The CDH has not proposed a guideline for americium-241.

On January 22, 1991, the CDH, EPA, and DOE signed an Interagency Agreement (IAG) that outlines the regulatory roles of the respective agencies, defines the interaction of the three parties, and defines the schedule of environmental restoration milestones. The IAG also grouped all of the sites undergoing environmental restoration into 16 Operable Units (OUs). These OUs, when assessed and remediated, should show an efficient expenditure of resources.

1.3 CONTAMINATED AREAS ASSESSED IN STUDY

This radiological assessment is concerned with two contaminated areas, one on-site and the other adjacent to the RFP. The first contaminated area is situated in OU 2, which is located in the southeastern and eastern portions of the main plant and buffer zone and consists of the 903 Pad, Mound, and East Trenches Areas (illustrated in Fig. 1.2). Referred to as the on-site area, it is located east of the 903 Pad in an unused field in the buffer zone of the RFP. The boundaries are assumed to be those used in an EG&G 1990 in situ study. The western boundary is adjacent to the 903 Pad and Lip Site areas, and the northern boundary is the east access road. Beyond this road is South Walnut Creek (OU 6), and beyond the southern boundary is Woman Creek (OU 5) and the Southern Interceptor Ditch (SID). East of the eastern boundary is Indiana Avenue, which runs along the eastern boundary of the RFP.

The second contaminated area is situated in OU 3, which consists of all contaminated soil outside of the RFP boundaries. Because the Remedial Investigation (RI) of OU 3 is still ongoing, the contamination boundaries have not been conclusively



determined. However, this assessment will only be concerned with two selected areas in OU 3 known as the Remedy Acreage (discussed in detail in Appendix A). This acreage consists of all of the contaminated soil in OU 3 that exceeds the CDH's plutonium guideline as illustrated in Fig. 1.3; it consists of a northern plot and a southern plot. These plots will be referred to as the northern and southern off-site areas or collectively as the off-site areas.

1.4 STATEMENT OF THE PROBLEM

The soil, sediments, groundwater, and surface water at both OU 2 and 3 are contaminated by radionuclides. Significant concentrations of americium-241 and various isotopes of plutonium have been found in the soil at OU 2, as have near-background levels of various isotopes of uranium and other radionuclide contaminants. Uranium-238 is the principal contaminant in the groundwater at OU 2, and various other isotopes of uranium and other radionuclides, including plutonium and americium, have been detected at slightly above background levels. The only known radionuclide contaminants present in the Remedy Acreage in OU 3 are plutonium and americium, and these radionuclides are limited to the soil and sediments.

DOE has both a commitment and a responsibility to protect the public and environment from undue risk from radiation exposure. Thus, these two OUs must be assessed to determine the risk to the public before their release from radiological control.

1.5 OBJECTIVES AND GOALS

This radiological assessment is intended to be a preliminary scoping model of the three contaminated areas in OU 2 and OU 3. This scoping assessment has four goals. These goals are to (1) determine the primary pathways for exposure (2) determine the

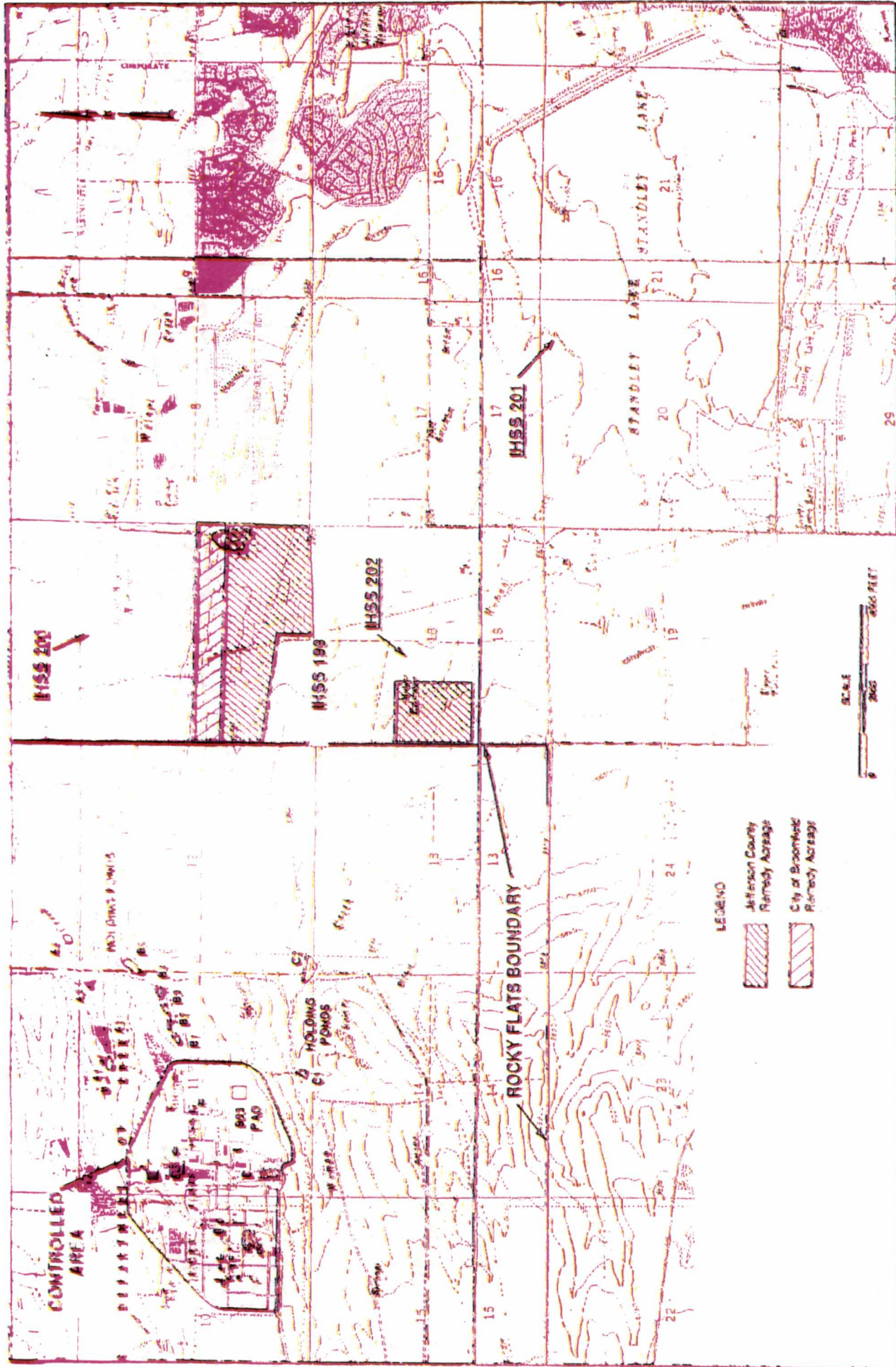


Figure 1.3. Location and Composition of Operable Unit 3

Source: "Final RFI/RJ Work Plan, Rocky Flats Plant, Operable Unit No. 3," EG&G Rocky Flats, Inc., February 1992

critical and/or sensitive data parameters (3) estimate the effective dose equivalent to the receptor in the hypothetical scenario and based on the results assess the need for remediation under DOE Order 5400.5, and (4) demonstrate how radionuclide soil guidelines are estimated for those contaminated areas where remediation may be necessary. These goals will be accomplished by predicting the radiation dose to human receptors residing in each of the contaminated areas who conform to a conservative pattern of living referred to as the family-farm scenario. The receptors and the potential exposure pathways as determined by the family-farm scenario are outlined and discussed in Chapter 3. If the computed annual radiation dose exceeds 100 mrem (millirem) in any year of the assessment (the assessment considers a 1000-year time horizon), then the area may not be released without remediation.

The radiation dose to the receptor in the family-farm scenario will be assessed by identifying and characterizing the following:

- potential exposure pathways identified under the RESRAD methodology;
- radionuclides present in each medium of concern; and
- simplified fate and transport modeling within environmental media, such as air and surface water dispersion, groundwater dispersion, radioactive decay, etc., as identified in the RESRAD methodology.

Only historical data is used in the assessment. The author has made no attempt to validate the data or take samples of his own.

2. METHODOLOGY

The methodology used to assess the three contaminated areas is based on the requirements and procedures outlined in Chapter 4 of DOE Order 5400.5, "Radiation Protection of the Public and the Environment." Chapter 4 presents radiological protection requirements and guidelines for cleanup of residual radioactive material; management of the resulting wastes and residues; and release of property. Information on the application of these guidelines and requirements are presented in DOE/CH 8901, "A Manual for Implementing Residual Radioactive Material Guidelines, A Supplement to the U.S. Department of Energy Guidelines for Residual Radioactive Material at Formerly Utilized Sites Remedial Action Program and Surplus Facilities Management Program Sites," June 1989. A computer model, RESRAD Version 4.2, written by Argonne National Laboratory under contract by DOE and based entirely on the procedures and methodology in DOE/CH 8901, is used for the computations.

"A guideline is defined as a radionuclide concentration or a level of radiation or radioactivity that is acceptable if a site is to be used without radiological restrictions. Guidelines are expressed as (1) concentrations of residual radionuclides in soil, (2) concentrations of airborne radon decay products, (3) levels of external gamma radiation, (4) levels of radioactivity from surface contamination, and (5) concentrations of residual radionuclides in air and water. . . . Generic guidelines for thorium and radium in soil, airborne radon decay products, external gamma radiation, surface contamination, and residual radionuclides in air and water are specified in the DOE guidelines" (Yu, 1992)..

Site-specific soil guidelines are derived by applying a basic radiation dose limit of 100 mrem/yr (as specified in the DOE guidelines) to a member (receptor) of a critical population group using an environmental pathway analysis with specific property data where available. This radiation dose is defined as the effective dose equivalent from external radiation plus the committed effective dose equivalent from internal radiation. Procedures and methods for these derivations are given in DOE/CH-8901.

"The controlling principles for all guidelines are (1) the annual radiation dose received by a member of the critical population group from the residual radioactive material - predicted by a realistic but reasonably conservative analysis and calculated as the effective dose equivalent - should not exceed the basic dose limit of 100 mrem/yr and (2) doses should be kept as low as reasonably achievable" (Yu, 1992).

DOE/CH-8901 requires that all significant exposure pathways for the critical population group be considered in deriving soil guidelines. These nine pathways include: (1) Direct exposure to external radiation from the contaminated soil material; (2) Internal radiation from inhalation of airborne radionuclides, including radon daughters; and (3) Internal radiation from ingestion of plant foods grown in the contaminated soil, meat and milk from livestock fed with contaminated fodder and water, drinking water from a contaminated well, fish from a contaminated pond, and contaminated soil (Yu, 1992).

These pathways are illustrated in Fig. 2.1. A graphic conceptual model of the pathways is shown in Fig. 2.2.

2.1 GUIDELINES FOR RESIDUAL RADIOACTIVE MATERIAL

Generic guidelines for concentrations of airborne radon decay products for existing occupied or habitable structures shall not exceed an annual average radon decay product concentration of 0.02 working levels (WL). Since no structures exist in the three contaminated areas and preliminary computations indicate that the dose from radon decay products is negligible, this pathway is not considered in the assessment (DOE, 1990).

Generic guidelines for external gamma radiation require that the average level inside a building or habitable structure on a site to be released without restrictions shall not exceed the background level by more than 20 μ R/h and shall comply with the basic dose limit. Because no structures exist in the three contaminated zone areas, this guideline is not applicable to the assessment. The guideline for surface contamination of

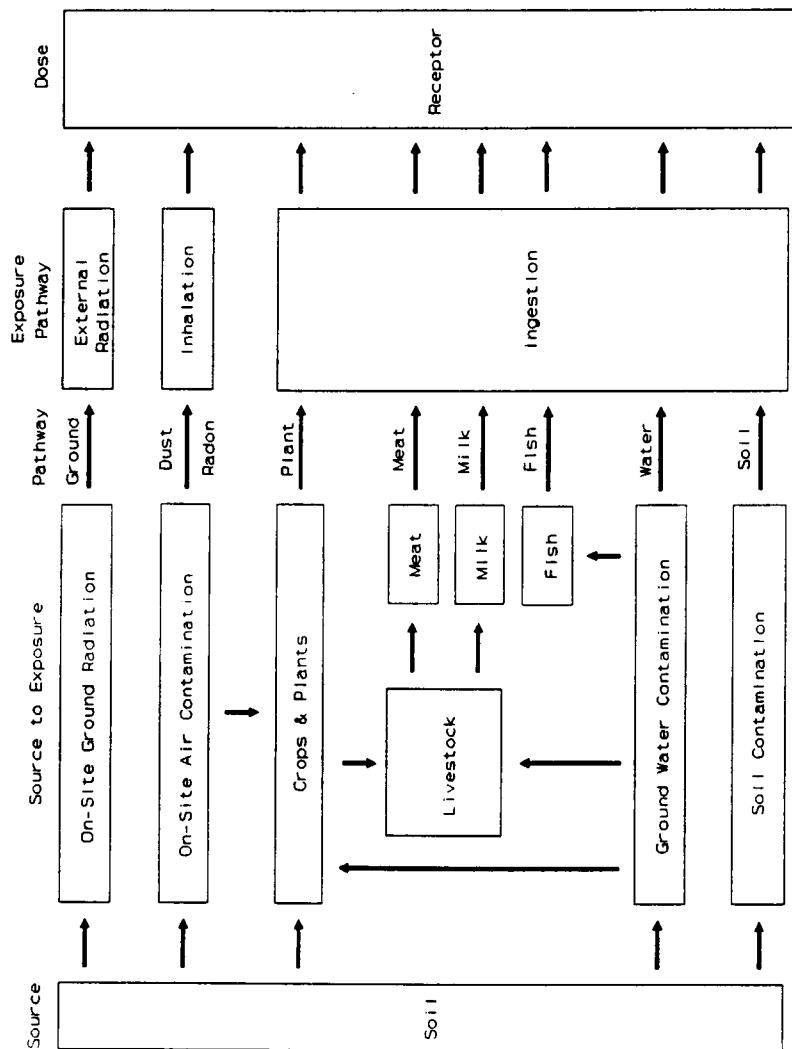


Figure 2.1. Schematic Representation of RESRAD Pathways.

Source:

Adapted from "Draft Manual For Implementing Residual Radioactive Material Guidelines," Yu, Zielen, et al, Argonne National Laboratory, February 1992.

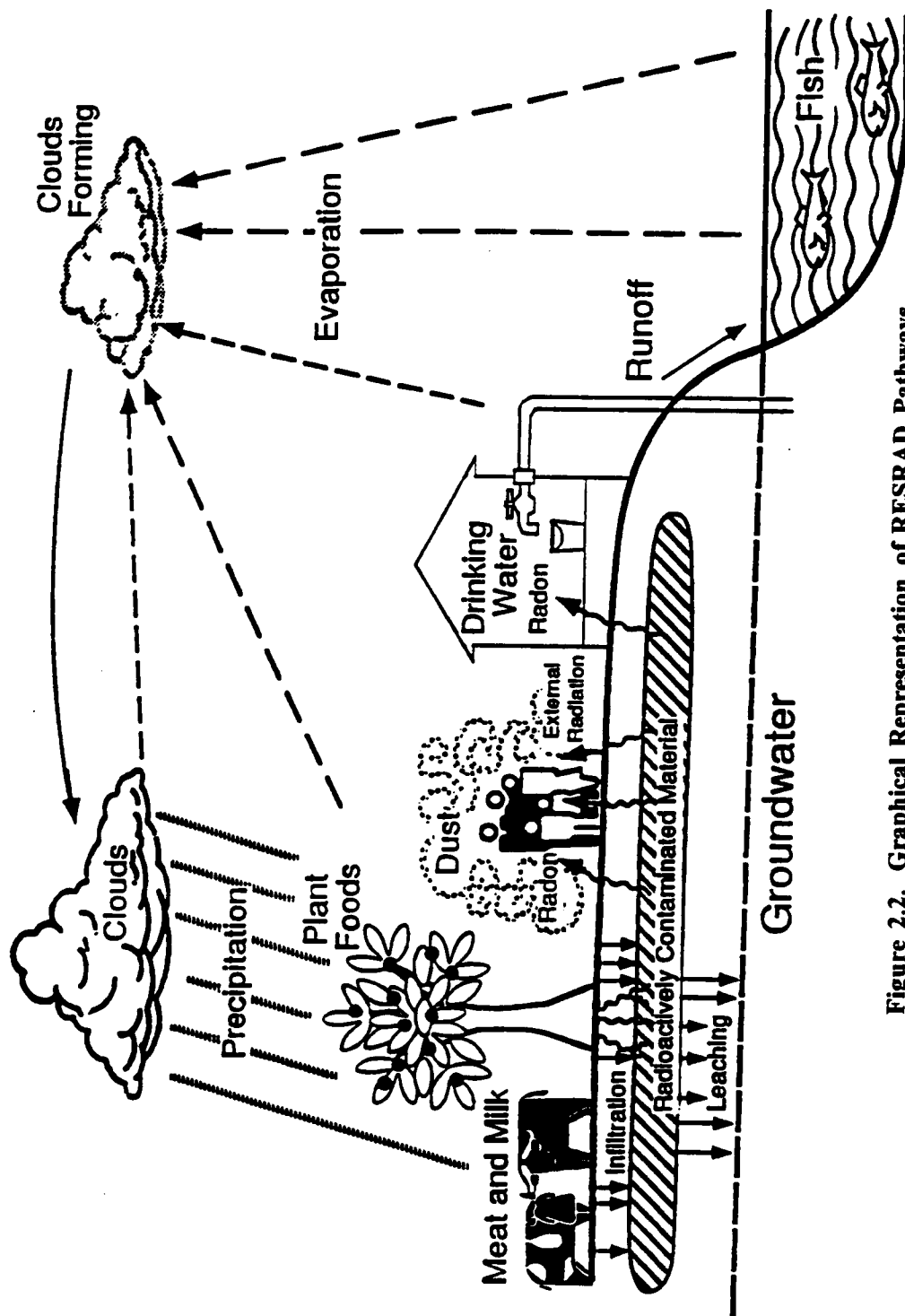


Figure 2.2. Graphical Representation of RESRAD Pathways

Source: "Draft Manual For Implementing Residual Radioactive Material Guidelines," Yu, Zielen, et al., Argonne National Laboratory, February 1992.

existing structures and equipment is also not applicable (DOE, 1990).

Last, generic guidelines for residual radionuclides in air and water require that exposure to the public shall not exceed 100 mrem/yr or any other applicable federal and/or state laws. Other applicable federal and/or state laws are beyond the scope of this thesis and are not considered (DOE, 1990).

2.1.1 Pathway Analysis

The pathway analysis for deriving soil concentration guidelines consists of four parts: (1) source analysis, (2) environmental transport analysis, (3) dose/exposure analysis, and (4) scenario analysis.

"Source analysis addresses the problem of deriving the source terms that determine the rate at which residual radioactivity is released into the environment. This rate is determined by the geometry of the contaminated zone, the concentrations of radionuclides present, the rates of ingrowth and decay of the radionuclides, and the rate of removal by erosion and leaching" (Yu, 1992). The source is an idealized contaminated zone of cylindrical shape within which radionuclides are present in above-background concentrations and are assumed to be uniformly distributed. The algorithms that are used to calculate the rates of ingrowth and decay of the radionuclides, and the rate of removal by erosion and leaching, are discussed in Appendices B and D. The data related to the source are discussed in Sect. 4.3.

"Environmental transport analysis addresses the problems of (1) identifying environmental pathways by which radionuclides can migrate from the source to a human exposure location and (2) determining the rate of migration along these pathways" (Yu, 1992). Potential environmental pathways through which radionuclides can migrate from the source to a human exposure location are presented above. The three main exposure

pathways through which radionuclides can enter the body are external radiation, inhalation, and ingestion. Potential pathways are determined by the scenario. The rate of migration along these environmental pathways is calculated by the environmental transport factor (ETF).

"Dose/exposure analysis addresses the problem of deriving dose conversion factors for the radiation dose that will be incurred by exposure to ionizing radiation" (Yu, 1992). The dose conversion factors (DCFs) used in the computations are presented in Appendix E.

"The parameters that control the rate of radionuclide release into the environment and the severity and duration of human exposure at a given location are determined by patterns of human activity referred to as exposure scenarios" (Yu, 1992).

2.1.2 Derivation of Guidelines for Residual Radioactive Material in Soil

"The basic criterion for releasing a site for use without radiological restrictions is the dose limit. The dose limit is converted to soil guidelines—specified as radionuclide concentrations—by means of dose/source ratios (DSRs) that are expressed in terms of three primary factors: DCFs, ETFs, and source factors (SFs)" (Yu, 1992). The following sections define these factors.

2.1.2.1 Radiological Release Criteria

RESRAD methodology states that the basic dose limit that must be satisfied before a site can be released for use without radiological restrictions is given in the following inequality,

$$H_E(t) \leq H_{EL}, \quad t_r \leq t \leq t_h \quad 2.1$$

where,

$H_E(t) =$	average annual committed effective dose equivalent received by a member of the critical population group at time t following the radiological survey of the site (mrem/yr),
$H_{EL} =$	basic dose limit (100 mrem/yr default),
$t_r =$	time at which the site is released for use without radiological restrictions following the radiological survey (1 year), and
$t_h =$	time horizon (1,000 years default) (Yu, 1992).

Hot spot criteria are considered in this assessment. DOE/CH/8901 presents the criteria for determining the presence of hot spots. However, for large hot spot areas (larger than 25 m²), which is typical of the contaminated areas as indicated in the 1990 In Situ Survey, the homogenous release criteria are sufficient.

2.1.2.2 Effective Dose Equivalent to the Receptor

The average annual effective dose equivalent received by the human receptor in the family-farm scenario from the i th principal radionuclide transported through the p th environmental pathway together with its associated decay products (mrem/yr), $H_{E,ip}(t)$, is given by the following equation,

$$H_{E,ip}(t) = DSR_{ip}(t) \times S_i(t) \quad 2.2$$

where,

$DSR_{ip}(t) =$	dose/soil-concentration ratio for the i th principal radionuclide and environmental pathway [(mrem/yr)/(pCi/g)], and
$S_i(0) =$	initial concentration of the i th principal radionuclide in a uniformly contaminated zone (pCi/g) (Yu, 1992).

Thus, the total annual effective dose equivalent to the target receptor is,

$$H_E(t) = \sum_i \sum_p H_{E,ip}(t) \quad 2.3$$

2.1.2.2.1 Dose/Source Concentration Ratios for Uniform Contamination

The dose/source concentration ratio describes the dose an individual would receive annually per unit of the particular isotope in soil. "The dose/source (D/S) concentration ratios are calculated by first expressing them as products of dose conversion factors [dose/exposure-parameter (D/E) ratios], environmental transport factors [exposure-parameter/source-concentration (E/S) ratios], and source factors (ratios of the concentration of a radionuclide at a given time to the initial concentration) (Yu, 1992)." The RESRAD manual gives the expression for the DSR as,

$$DSR_{ip}(t) = \sum_j DCF_{j,x(p)} \times ETF_{jp}(t) \times SF_{ij}(t) \quad 2.4$$

where,

- DCF_{j,x(p)} = dose conversion factor for the *j*th principal radionuclide and *x(p)*th exposure pathway [(mrem/yr)/(pCi/cm³) for external radiation from the contaminated zone; mrem/pCi for internal radiation from ingestion or inhalation of radionuclides],
- ETF_{jp}(*t*) = environmental transport factor for the *j*th principal radionuclide and *p*th environmental pathway at time *t* (g/cm³ for external radiation from the contaminated zone; g/yr for internal radiation from ingestion or inhalation of radionuclides),
- 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 present initially (dimensionless),
- x(p)* = index label for exposure pathways, which is a function of the environmental pathway *p* [for

p=1 (external radiation from the ground),
x(p)=1; for p=2 and 3 (inhalation of dust
and radon), x(p)=2; and for p=4,5,6,7,8, and
9 (ingestion of plants, meat, milk, fish, water,
and soil, respectively), x(p)=3],

p = index label for environmental pathways, and

i,j = index labels for principal radionuclides (Yu, 1992).

2.1.2.2.2 Dose Conversion Factors

The RESRAD manual defines the dose conversion factor (DCF) as,

$$DCF_{ix} = \frac{H_{E,ix}}{E_{ix}} \quad 2.5$$

where,

$H_{E,ix}$ = annual effective dose equivalent resulting from exposure to external radiation (x=1) from the *i*th principal radionuclide and its associated radionuclides (mrem/yr) or the annual committed effective dose equivalent resulting from exposure for 50 years to internal radiation from the amount of the *i*th principal radionuclide and its associated radionuclides inhaled (x=2) or ingested (x=3) in 1 year (mrem/pCi), and

E_{ix} = 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/cm³ for external radiation [x=1] from the contaminated zone; pCi/yr for internal radiation from inhalation [x=2] or ingestion [x=3]) (Yu, 1992).

An internal dose conversion factor for any radionuclide includes the contribution from ingrowth following ingestion or inhalation. The internal dose conversion factor for a principal radionuclide includes, in addition, the contribution from inhalation or ingestion of associated radionuclides along with the principal radionuclide. The additional contribution is significant

only for associated radionuclides with half-lives that are not small compared to the biological half-life. The dose conversion factor for external radiation for a principal radionuclide is defined here to include the dose from all of its associated radionuclides, which are assumed to be in secular equilibrium (Yu, 1992).

The dose conversion factors used in this dose assessment are provided in the RESRAD manual and are presented for the five isotopes of plutonium and americium-241 in Tables E.1, E.4, and E.5 for each individual environmental-exposure pathway.

2.1.2.2.3 Environmental Transport Factors

The RESRAD manual defines the ETF as the time-dependent ratio of,

$$ETF_{ip}(t) = \frac{E_{ip}(t)}{S_i(t)} \quad 2.6$$

where,

$E_{ip}(t)$ = exposure parameter value at time t for the i th principal radionuclide (or radiation therefrom) transported through the p th environmental pathway (pCi/cm³ for external radiation from the contaminated zone; pCi/yr for internal radiation),

p = index label for environmental pathways, and

$S_i(t)$ = average concentration of the i th principal radionuclide in a uniformly contaminated zone at time t (pCi/g) (Yu, 1992).

The exposure parameter for external radiation from the contaminated zone is the concentration of the i th principal radionuclide 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 i th principal radionuclide that is inhaled or ingested after migrating through the p th environmental pathway. There are only two internal exposure pathways (inhalation and ingestion); several environmental pathways can contribute to each (Yu, 1992).

Section 4.5 contains the equations for calculating the ETFs for all of the environmental-exposure pathways.

2.1.2.2.4 Source Factors

Source factors are correction factors for the source term (the radionuclide concentration in the contaminated zone). These factors correct for the contribution from ingrowth and the removal resulting from radioactive decay and leaching. "If leaching is negligible, the source factor reduces to a factor that accounts for ingrowth and decay only. This factor is called the ingrowth-and-decay factor, $ID_{ij}(t)$ " (Yu, 1992).

Radionuclides are divided into two groups: those with half-lives longer 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 radionuclides and that the leach rate of the associated radionuclides is the same as the leach rate of their principal radionuclide. Hence, only the source factors for the principal radionuclides need to be calculated (Yu, 1992).

Let $S_{ii}(0)$ be the initial concentration of the i th principal radionuclide and let $S_{ij}(t)$ be the concentration at time t of the j th principal radionuclide that results from ingrowth from the initial inventory of the i th principal radionuclide. $S_{ii}(t)$ is the concentration of the undecayed portion that is available for leaching of the i th principal radionuclide. $[S_{ii}(t)]$, which does not include any contribution from ingrowth, should be distinguished from

$$S_i(t) = \sum_j S_{ij}(t)$$

which does include the contribution from ingrowth.] $S_{ii}(0) = 0$ unless $i=j$, and $S_{ij}(t) = 0$ unless $i=j$ or the j th principal radionuclide is a decay product of the i th principal radionuclide. The source factor is defined as,

$$SF_{ij}(t) = \frac{S_{ij}(t)}{S_i(0)} \quad 2.7$$

The initial values of the source factors are $SF_{ij}(0) = 0$ unless $i=j$, and $SF_{ii}(0) = 1$. For $t>0$, $SF_{ij}(t) = 0$ unless $i=j$ or the j th principal radionuclide is a decay product of the i th principal radionuclide. When $i=j$, the inequality $1 > SF_{ii}(t) > 0$ will be satisfied for $t>0$ (Yu, 1992).

"Equations for calculating source factors and ingrowth-and-decay factors are given below. Branching radionuclides are a common complication, and there are four possible cases to consider: (1) only associated radionuclides are involved; (2) a principal radionuclide parent branches to associated radionuclide daughters; (3) an associated radionuclide parent branches to at least one principal radionuclide daughter; and (4) a principal radionuclide parent branches to at least one

principal radionuclide daughter" (Yu, 1992).

Cases 1 and 2, described above, cover most of the radionuclides in the RESRAD code.

Case 3 does not occur at all. Assuming that all associated radionuclides are in equilibrium with their principal radionuclide parents, branching need not be considered in deriving source factors and ingrowth-and-decay factors.

There are three Case 4 branching principal radionuclides in the RESRAD code; europium-152, plutonium-241, and curium-243. Because plutonium-241 is the only radionuclide of the above three that is a contaminant in OU 2 and OU 3 and the initial concentrations of plutonium-241 are negligible, Case 4 branching does not occur in this assessment.

Assuming a first-order ion-exchange leaching, the equation for ingrowth and decay and leaching of a nonbranching chain is,

$$\frac{dA_k}{dt} = \lambda_k A_{k-1} - (\lambda_k + L_k)A_k \quad 2.8$$

where,

A_k = activity concentration of the k th radionuclide in the chain (pCi/g),

λ_k = $\ln(2)/T_{1/2,k}$ = radioactive decay constant of the k th radionuclide (yr^{-1}),

$T_{1/2,k}$ = radioactive decay half-life of the k th radionuclide (yr), and

L_k = leach rate of the k th radionuclide (yr^{-1}) (Yu, 1992);

The solution to Eq 4.8 is

$$A_k(t) = \sum_{i=0}^k a_{ki} + \exp[-(\lambda_i + L_i) t] \quad 2.9$$

where,

$$a_{00} = A_0(0), \quad 2.10$$

$$a_{kl} = \left[\frac{\lambda_k}{(\lambda_k + L_k - \lambda_l - L_l)} \right] a_{(k-1)l}, \quad l = 0, 1, \dots, k-1; \quad 2.11$$

and

$$a_{kk} = A_k(0) - \sum_{l=0}^{k-1} a_{kl} \quad 2.12$$

The source factor $SF_{ij}(t)$ can be calculated as,

$$SF_{ij}(t) = \frac{A_{i(j)}(t)}{A_0(0)} \quad 2.13$$

where $l(ij)$ is the sequence number for the j th principal decay product of the i th principal radionuclide, numbered from the i th principal radionuclide [$l(ii) \equiv 0$]. The ingrowth-and-decay factor $ID_{ij}(t)$ when the leach rates L_1 and L_k are set to zero.

3. SITE CHARACTERIZATION

3.1 DESCRIPTION OF CONTAMINATED AREAS

A complete description of the Rocky Flats Plant, OU 2, and OU 3 is provided in Appendix A. A complete history of both OUs is also presented.

3.2 SITE PHYSICAL CHARACTERISTICS

3.2.1 Geology

RFP is located along the eastern edge of the southern Rocky Mountain region immediately east of the Colorado Front Range and the Continental Divide. The plant is located on a broad terrace sloping approximately 1 degree to the east between the stream-cut valleys of North Walnut Creek and Woman Creek, and it rests at an average elevation of approximately 5,950 ft above mean sea level. The terrace is capped with overlapping alluvial fan deposits of Quaternary age known as Rocky Flats Alluvium, which was deposited from outwash approximately 1 to 1.5 million years ago. This outwash occurred as water from melting glaciers (located 5 miles to the west at higher elevations in the Front Range) flowed out of the mouth of Coal Creek Canyon. These alluvial fans extend about 5 miles east of the Front Range, where gentle slopes break into low rolling hills. More recent surficial deposits occur topographically below the Rocky Flats Alluvium and include Verdos Alluvium, Slocum Alluvium, colluvium, and Valley Fill Alluvium. These various surficial materials in the vicinity of the RFP are illustrated in Fig. 3.1 (EG&G, 1991a; EG&G, 1991b; DOE, 1992).

Rocky Flats Alluvium lies beneath most of the structures at the RFP and is thickest (approximately 100 ft) at the western edge of the plant. The alluvium gradually thins to the east until it terminates approximately 0.5 to 1.5 miles west of the eastern

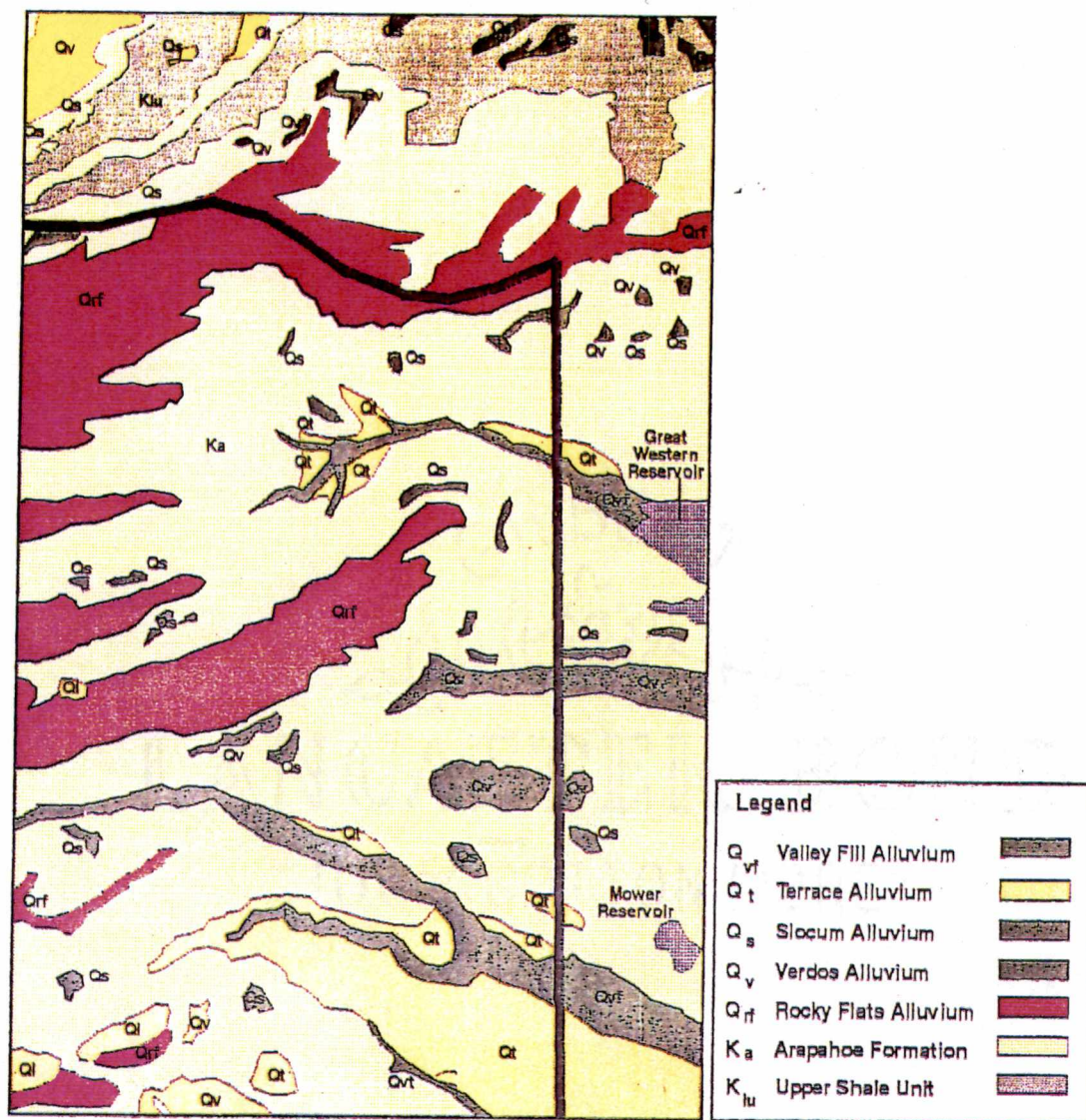


Figure 3.1. Surficial Geology Map

Source: Adapted from "Draft Rocky Flats Plant Surface Water Management Plan," EG&G Rocky Flats, Inc., March 1991.

boundary of the plant. It underlies much of the on-site contaminated area and is thickest (approximately 40 to 45 ft) along the western edge. The alluvial surface declines approximately 300 ft for a distance of 3.4 miles, and the slope is 88 ft per mile (1-2%) (EG&G, 1991b). "The Rocky Flats Alluvium is composed of yellowish brown to reddish brown, angular to subrounded, poorly sorted, coarse, bouldery gravel in a sand matrix with lenses of clay, silt, and sand and varying amounts of caliche. Pebbles, cobbles, and boulders are composed primarily of quartzite but include lesser amounts of schist, gneiss, granite, pegmatite, sandstone, and siltstone" (EBASCO, 1992).

Colluvium deposits are found on the hillside south of the 903 Pad and East Trenches Areas, and on the hillside north of the Mound and East Trenches Areas. They comprise a significant portion of the surficial soil for the on-site contaminated area. These deposits also extend into OU 3 and comprise the surficial material for much of the remedy acreage. Colluvium (also referred to as slope wash) is a surficial deposit present on the sides and at the bases of hills and slopes. It is the product of erosional processes and is comprised of a mixture of Rocky Flats Alluvium and bedrock fragments. This surficial layer lies in the topographically lower areas between the Rocky Flats Alluvium and the Valley Fill Alluvium and rarely exceeds a thickness of 2 to 3 ft (EG&G, 1991a; EG&G, 1991d).

Valley Fill Alluvium deposits (sediments) occur along the bottoms of major stream channels. It is found in the drainage of Woman Creek south of the 903 Pad and East Trenches Areas and in the South Walnut Creek drainage north of the Mound Area. These deposits extend into OU 3, where Woman Creek drains into Standley Lake, and South Walnut Creek drains into Great Western Reservoir. The Valley Fill Alluvium deposits in the South Walnut Creek extend north of the northern off-site contaminated

area. However, the deposits in the Woman Creek drainage comprise a significant portion of the surficial material for the southern off-site contaminated area. Valley Fill Alluvium is composed of light brown to brownish gray humic clay, silt, sand, and pebbly sand with silty and cobbly gravel lenses. Thickness of the deposits is generally less than 10 ft in the OU 2 and OU 3 areas (EG&G, 1991a; EG&G, 1991d; EBASCO, 1992).

Verdos and Slocum Alluviums are post-Rocky Flats undifferentiated terrace alluvium deposited on pediments topographically below the Rocky Flats Alluvium but higher than channel and terrace deposits in modern streams. Verdos Alluvium comprises part of the surficial material for the northern off-site contaminated area. These deposits consist principally of light to moderate brown, clayey coarse gravel and coarse sand. Pebbles and cobbles are mostly quartzite. Thicknesses range from 10 to 50 ft (EG&G, 1992b; EBASCO, 1992).

Underlying the Rocky Flats Alluvium are several bedrock formations that comprise part of the Denver Basin. These bedrock formations are the Arapahoe, Laramie, and Fox Hills Sandstone. Figures 3.2 and 3.3 illustrate generalized cross-sections of the geology underlying the plant and the surrounding area. Figure 3.4 provides a generalized stratigraphic cross-section of the geology underlying RFP.

The Arapahoe Formation is the uppermost bedrock formation in the vicinity of the RFP. It is Cretaceous-aged and approximately 250-ft thick. The formation consists of fluvial claystones with interbedded sandstones, siltstones, and occasional lignite deposits. A fluvial depositional environment that included meandering streams flowing east-southeast from the Front Range Uplift created the Arapahoe Formation. The sandstone bodies consist of five intervals of meandering lenses occurring at various depths. Most of the sandstone is very fine- to medium-fine grained, poorly to moderately sorted,

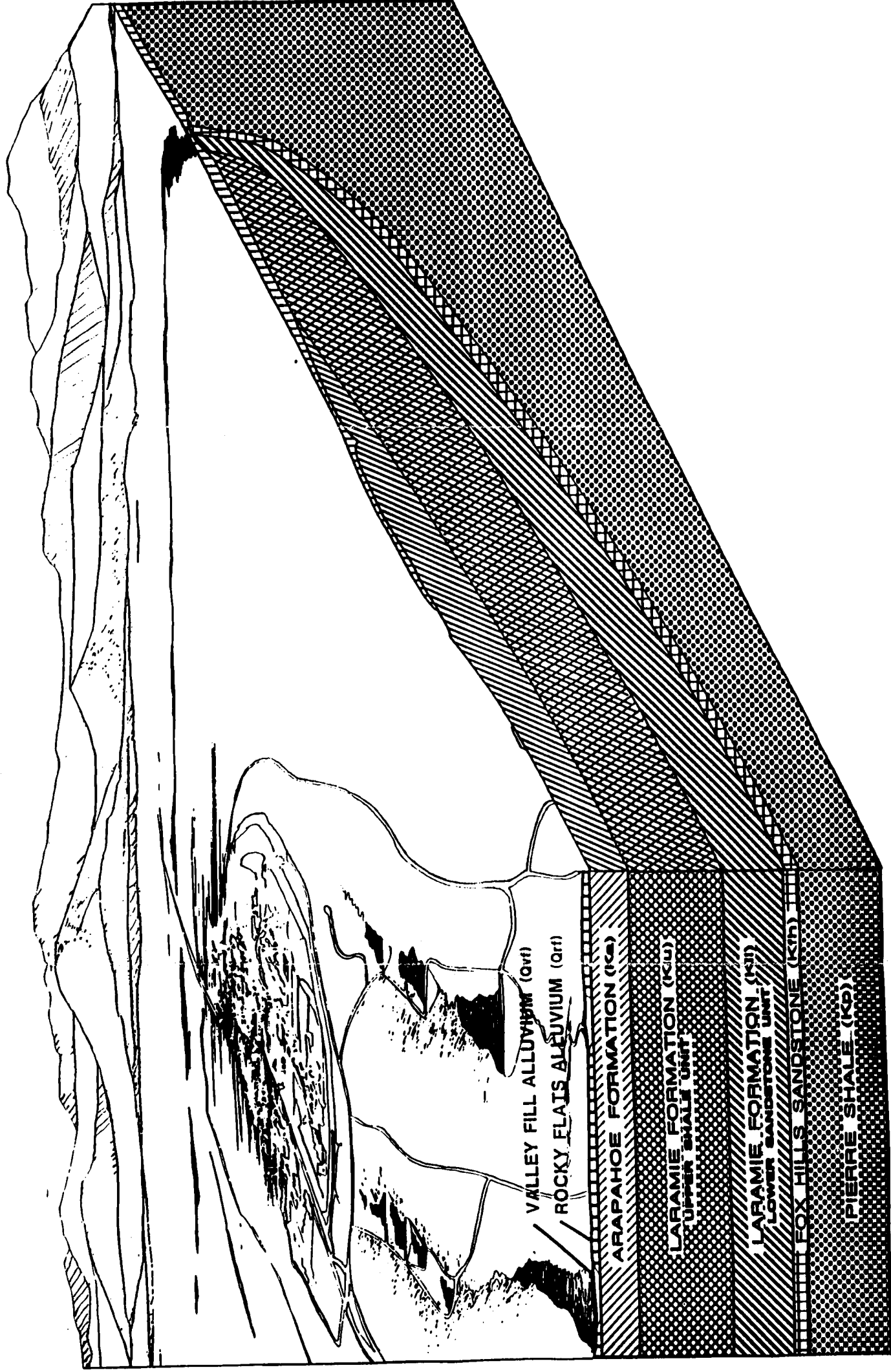


Figure 3.2. Geologic Formations Underlying the Rocky Flats Plant

Source: Adapted from "Draft Rocky Flats Plant Surface Water Management Plan," EG&G Rocky Flats, Inc., March 1991.

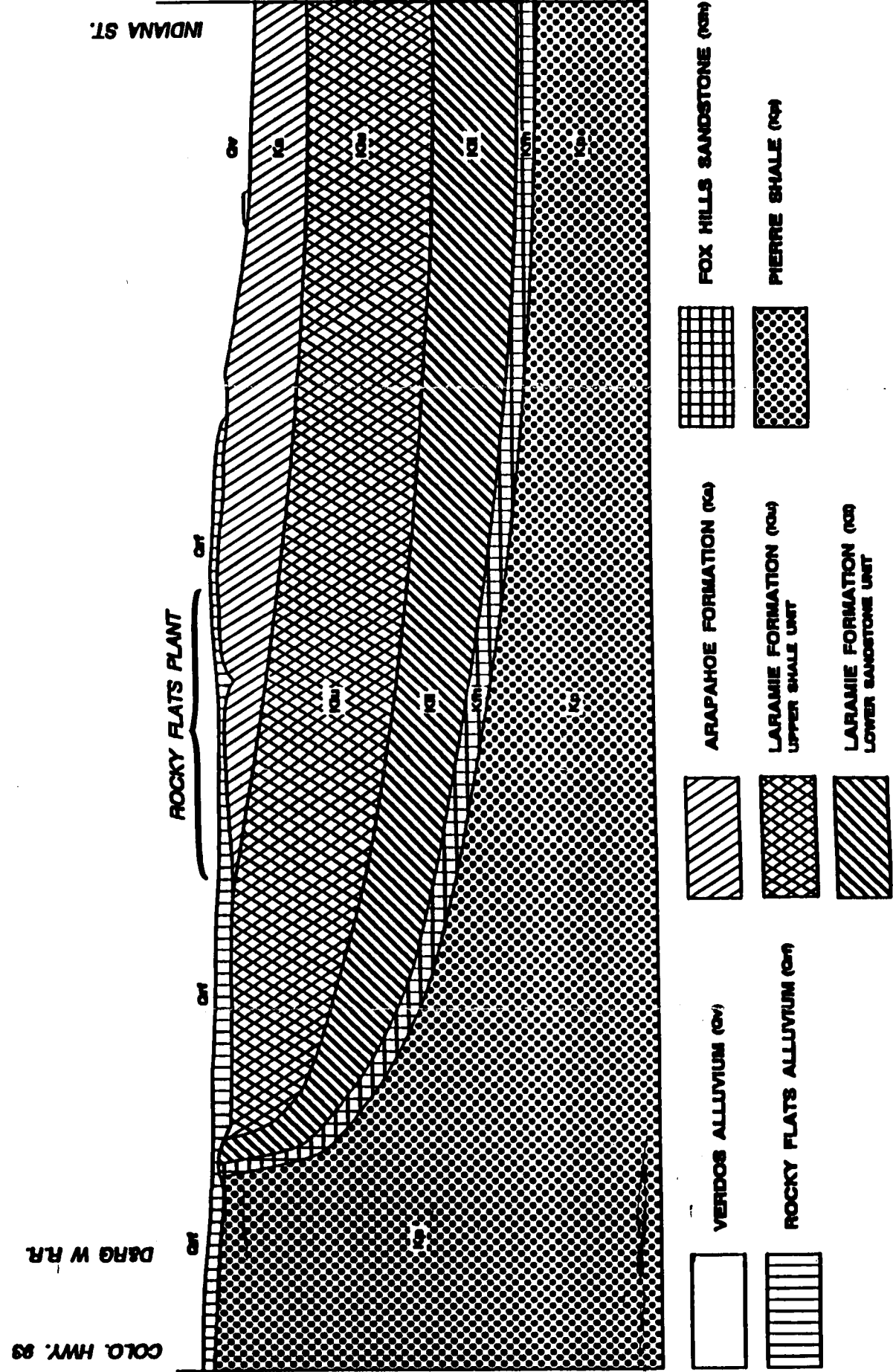


Figure 3.3. Rocky Flats Generalized Geologic Cross-Section

Source: Adapted from "Draft Rocky Flats Plant Surface Water Management Plan," EG&G Rocky Flats, Inc., March 1991.

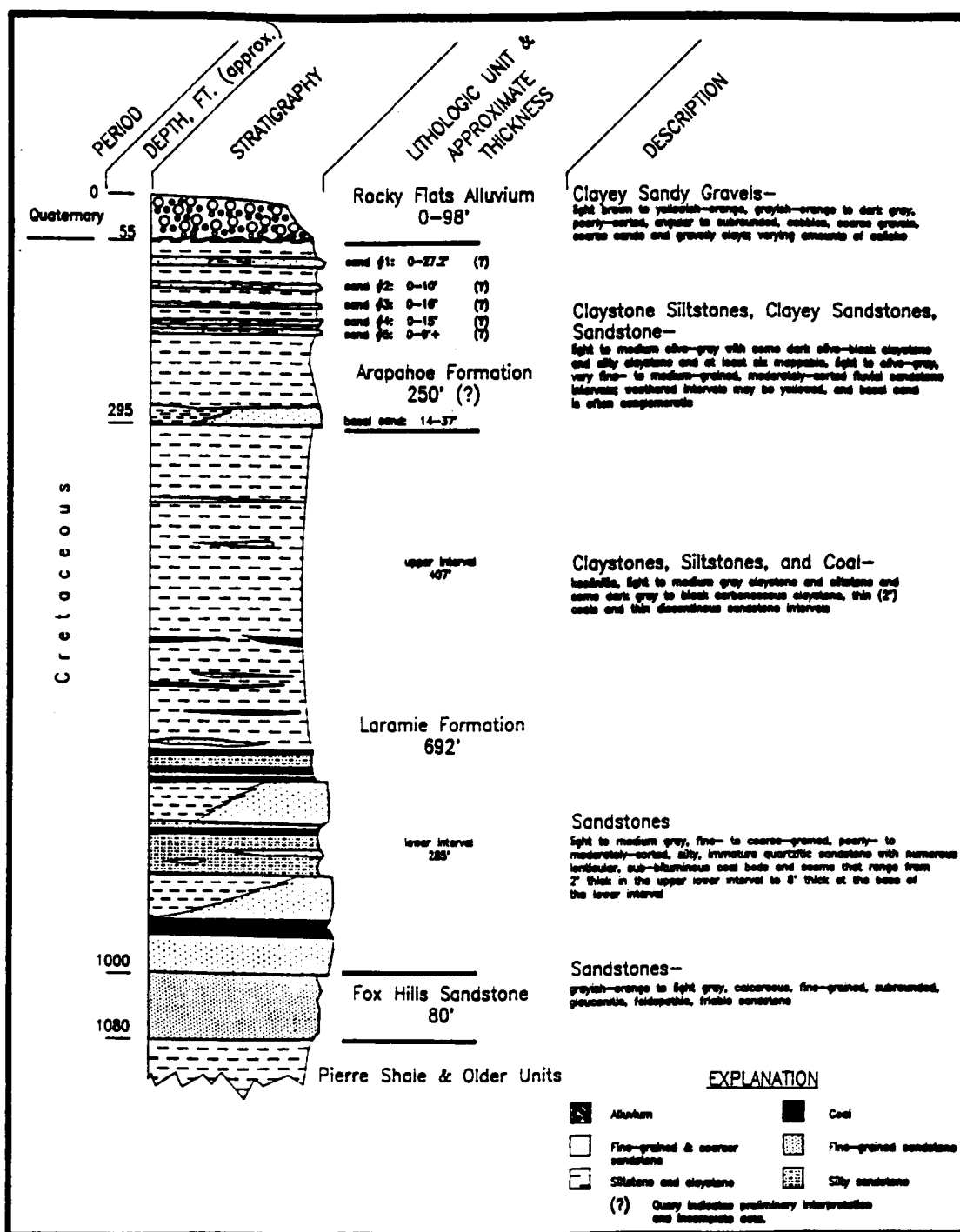


Figure 3.4. Local Stratigraphic Section of the Rocky Flats Plant

Source: "Final Phase II RFI/RI Work Plan (Bedrock), Rocky Flats Plant, 903 Pad, Mound, and East Trenches Areas (Operable Unit 2)," EG&G Rocky Flats, Inc., June 1991.

subangular to subrounded, silty and clayey (EG&G, 1991a; EG&G, 1991b; DOE, 1991d).

The Laramie Formation underlies the Arapahoe Formation. It is 800-ft thick at the plant site and consists of two distinct intervals: 500 ft of claystone overlaying 300 ft of sandstone and coal. "The sandstones are light to medium gray, fine- to coarse-grained, poorly sorted, subangular, silty, quartzitic, and containing grains of black chert. Clay, mica, and carbonaceous material are also present. The claystones are dominantly light to medium gray and kaolinitic; however, dark gray to black carbonaceous claystones are also present" (EG&G, 1991d).

The Fox Hills Sandstone underlies the Laramie Formation. It is approximately 75- to 125-ft thick under the plant site. "The dominant lithology is a calcareous, fine-grained, subrounded, friable, glauconitic, feldspathic sandstone with thin beds of siltstone and claystone" (EG&G, 1991d).

3.2.2 Groundwater Hydrology

As shown in Figs. 3.2 and 3.3, the geology of interest at RFP consists of four bedrock formations overlaid by surficial material. Groundwater is present under unconfined conditions in the surficial (Rocky Flats Alluvium, colluvium, and Valley Fill Alluvium) units, under semi-confined conditions in shallow bedrock (Arapahoe Sandstone) units, and in deeper bedrock sandstones (Fox Hills Sandstone) (EG&G, 1991b).

3.2.2.1 Hydrology of Surficial Materials

Unconfined groundwater flow occurs in the Rocky Flats Alluvium, which is relatively permeable. Recharge to the alluvium occurs from infiltration of precipitation and snowmelt, and water losses result from ditches, streams, and ponds that have cut into the alluvium. General water movement in the Rocky Flats Alluvium is from west to east and toward the drainages (groundwater flow is also controlled by paleochannels in the top

of the bedrock). The water table in the Rocky Flats Alluvium rises in response to recharge during the spring and declines during the rest of the year, and the shallow groundwater flow also changes in response to precipitation affecting streams and ditch flow. Discharge from the alluvium occurs at minor seeps and springs in the colluvium that covers the alluvium and bedrock contact along the edges and sideslopes of the terrace. Groundwater in colluvial materials south of the 903 Pad and East Trenches Areas discharges to the South Interceptor Ditch (SID), and groundwater in valley fill materials discharge to Woman or South Creeks. Because OU 2 is situated on a terrace of Rocky Flats Alluvium that thins out to the east, it does not directly supply water to wells located downgradient of Rocky Flats (EG&G, 1991b).

As previously discussed, various other alluvial deposits (colluvium and Verdos, Slocum, and Louviers Alluvia) occur topographically below the Rocky Flats Alluvium in the plant drainages. Unconfined groundwater flow occurs in these surficial units. Recharge is from precipitation, percolation from streams and ditches during periods of surface-water runoff, and by seepage from the Rocky Flats Alluvium. Discharge is by seepage into other geological formations and streams, and by evaporation where the water table approaches the ground surface. The direction of groundwater flow is generally downslope through colluvial materials and then, along the course of the stream, in valley fill materials. During periods of high surface water flow, water is lost to bank storage in the Valley Fill Alluvium and returns to the stream after the runoff subsides (EG&G, 1991b).

"Hydraulic conductivity values were estimated for surficial materials based on drawdown-recovery tests performed in 1986 on wells drilled that year during the initial site characterization and from slug tests performed on selected 1986 and 1987 wells during the

1987 Phase I Remedial Investigation" (EG&G, 1991c). The mean hydraulic conductivity for the Rocky Flats Alluvium based on all hydraulic tests was 4×10^{-4} cm/s. The reported values ranged from 4×10^{-5} cm/s at Well 3986 to 5×10^{-2} cm/s at Well 4286. An average groundwater velocity was calculated as 85 ft per year (26 m per year), assuming an average horizontal gradient of 0.02 feet/foot and an effective porosity of 0.1. The mean hydraulic conductivity for the Woman Creek Valley Fill Alluvium, based upon the same series of tests, is 7×10^{-4} cm/s. The reported values ranged from 5×10^{-5} cm/s at Well 6886 to 3×10^{-3} cm/s at Well 6586. An average groundwater velocity was calculated as 145 ft per year (44 m per year), assuming an average horizontal gradient of 0.02 feet/foot and an effective porosity of 0.1 (EG&G, 1991c).

South Walnut Creek Valley Fill is less conductive than that along Woman Creek, based on lithologic descriptions and hydraulic conductivity tests of Well 3586. A drawdown-recovery test and a slug test have been performed in Well 3586. The hydraulic conductivity of South Walnut Creek Alluvium calculated from the drawdown-recovery test was 9×10^{-5} cm/s. Results of the slug test indicated a hydraulic conductivity of 1×10^{-4} cm/s. Assuming a mean conductivity of 9.5×10^{-5} cm/s, an effective porosity of 0.1, and an average gradient of 0.02 feet/foot, the average linear velocity of groundwater in South Walnut Creek Valley Fill is estimated to be about 20 ft/yr (6.1 m/yr) (EG&G, 1991c).

The Draft Rocky Flats Surface Water Management Plan gives a representative hydraulic conductivity of 0.17 ft/day (6×10^{-5} cm/sec) for the surficial alluvium unit (Rocky Flats Alluvium, Valley Fill Alluvium, and colluvium) with a range of 0.3 to 0.003 ft/day (10^{-4} to 10^{-6} cm/s).

3.2.2.2 Hydrology of Bedrock Materials

Because of their relatively high permeability, the meandering lenticular sandstones contained within the claystones (i.e., the basal formation) provide the greatest potential for groundwater flow in the Arapahoe Formation. It is recharged by groundwater movements from overlying surficial deposits and by leakage from streams (EG&G, 1992b).

The main recharge areas are under the Rocky Flats Alluvium, although some recharge from the colluvium and valley fill alluvium is likely to occur along the stream valleys. Recharge is greatest during the spring and early summer when rainfall and stream flow are at a maximum and water levels in the Rocky Flats Alluvium are high. Groundwater movement in the Arapahoe Formation is generally toward the east, although flow within individual sandstones is not fully characterized at this time. Regionally, groundwater flow in the Arapahoe Formation is toward the South Platte River in the center of the Denver Basin...(EG&G, 1992b).

The Laramie Formation, which underlies the Arapahoe Formation, consists of two units, a thick upper claystone and a lower sandstone. The claystone unit has a thickness in excess of 700 ft and a very low hydraulic conductivity. Based on these two factors, the U.S. Geological Survey has concluded that RFP operations will not affect any units below the upper claystone unit of the Laramie Formation (EG&G, 1992b).

The lower sandstone unit of the Laramie Formation and the underlying Fox Hills Sandstone comprise a regionally important aquifer in the Denver Basin known as the Laramie-Fox Hills Aquifer. Aquifer thickness ranges from 200 to 300 ft near the center of the basin. These units subcrop west of the Plant and can be seen in clay pits excavated through the Rocky Flats Alluvium. "The steeply dipping beds of these units west of the Plant (approximately a 50° dip) quickly flatten to the east (less than 2° dip) based on preliminary results of the high resolution seismic reflection study. . . ." (EG&G, 1992b).

3.2.3 Surface Water Hydrology

RFP has four main drainages, shown in Fig. 1.1. North Walnut Creek, South Walnut Creek, Rock Creek, and Woman Creek are all ephemeral streams. Rock Creek drains the northwest corner of the plant and flows northwest through the buffer zone until it flows into Coal Creek. North and South Walnut Creeks and an unnamed tributary drain the northern portion of the plant. These three tributaries join in the buffer zone to form Walnut Creek, which flows into Great Western Reservoir approximately one mile

downstream from the confluence. Woman Creek drains the southern RFP buffer zone and flows to the east into Standley Lake. Both Walnut Creek and Woman Creek drainages are important because they handle the majority of the drainage and empty into reservoirs that provide drinking and irrigation water. A more detailed discussion of these two drainages is presented below (EG&G, 1991b).

3.2.3.1 Walnut Creek

The headwaters area of South Walnut Creek was filled during construction of RFP facilities. As a result, flow originates from a buried culvert located in the east-central portion of OU 2, west of Building 991. Flow in the upper reach of South Walnut Creek is directed to the south of Building 991 and under the Protected Area (PA) fence by a buried, corrugated metal culvert. The culvert outlet is located in the South Walnut Creek drainage approximately 500 ft downgradient of the PA fence near the discharge of the sewage treatment plant. A concrete culvert and a second corrugated metal culvert also discharge into the South Walnut Creek drainage just downgradient of the PA fence and north of the Mound Area. The flow from the concrete culvert originates as seepage from the hillside south of Building 991 and flows into a ditch along the slope. The corrugated metal culvert drains plant runoff that collects in a drainage south of the PA. The combined flow then enters the South Walnut Creek detention pond system (EG&G, 1991a).

Below the detention ponds, North and South Walnut Creek and an unnamed tributary converge to form Walnut Creek, which is diverted from and routed around Great Western Reservoir by the Broomfield Diversion Canal.

The South Walnut Creek detention pond system consists of five ponds (B-1, B-2, B-3, B-4, and B-5) that retain surface water runoff and RFP discharges for flood control, monitoring, and treatment prior to downstream release. All flow in the pond system is eventually detained in

Pond B-5, where it is treated and monitored prior to discharge. Water is discharged from Pond B-5 in accordance with the Plant NPDES permit (discharge point 006). Ponds B-1 and B-2 are reserved for spill control, surface water runoff, or treated sanitary waste of questionable quality. Pond B-3 is used as a holding pond for sanitary sewage treatment plant effluent. The historical discharge of Pond B-3 was a spray irrigation system located in the vicinity of the East Trenches; however, this practice has been terminated and current Pond B-3 discharge is routed to Pond B-4. In addition to Pond B-3 discharge, Ponds B-4 and B-5 receive surface water runoff from the central portion of the RFP. The surface water runoff received by Pond B-4 is collected by the Central Avenue Ditch and the South Walnut Creek Drainage (EG&G, 1991a).

3.2.3.2 Woman Creek

Woman Creek is located south of the Plant, with headwaters in largely undisturbed Rocky Flats Alluvium. Runoff from the southern part of the Plant is collected in the SID located north of the creek and delivered downstream to Pond C-2 (see Fig. 2-2). Pond C-1 (upstream of C-2) receives stream flow from Woman Creek. Flow in Woman Creek is also influenced by diversion of water from Rocky Flats Lake into the creek by local landowners. The discharge from Pond C-1 is diverted around Pond C-2 into the Woman Creek channel downstream. Water in Pond C-2 is treated and monitored prior to discharge. Discharge from Pond C-2 is in accordance with the Plant's NPDES permit (discharge point 007). Historically, discharge from Pond C-2 has been to Woman Creek; however, since October of 1989, treated water is being pumped to the South Walnut Creek drainage and flows off-site via the Broomfield Diversion Canal. Flow in Woman Creek and the SID is intermittent. This pattern has been observed by field investigation crews since 1986 (EG&G, 1991a).

3.3 NATURE AND EXTENT OF CONTAMINATION

Radionuclide contamination of the environment surrounding RFP is the result of past effluent releases and waste disposal practices during the operation of the plant.

Plutonium and americium are the principal radionuclide contaminants. Uranium, tritium, strontium, and cesium are also present in varying concentrations. Sections 3.2.1 and 3.2.2 discuss radionuclide contamination of soil and sediments, and groundwater respectively.

3.3.1 Soil and Sediments

Two sources are used to evaluate the radionuclide contamination in the on-site area; borehole sampling taken for the Phase I Remedial Investigation and the 1990 In-Situ Survey. Both sources indicate plutonium and americium contamination of the soil in the 903 Pad, Mound, and East Trenches Areas. The 1991 Annual Remedy Acreage Survey also indicates plutonium contamination of the off-site (Remedy Acreage). Americium contamination of the off-site areas is assumed with the same proportion to plutonium as for the on-site area.

Pu-239 is a fissile material used in the construction of nuclear weapons. It is manufactured in a reactor, where fertile U-238 is exposed to neutrons and transformed through the process of neutron absorption. Pu-238, Pu-240, Pu-241, and Pu-242 are byproducts of the process. Am-241 is the daughter product from the decay (14.4 year half-life) of Pu-241.

Plutonium contamination consists of almost entirely Pu-239 and Pu-240. Pu-238, Pu-241, and Pu-242 are also present. However, these three radionuclides consist of less than 1% of the total amount of plutonium present. Americium contamination strictly consists of Am-241. Plutonium and americium are significantly elevated in the 903 Pad Area and slightly elevated in the Mound and East Trenches Areas. The In-Situ Survey provides more detailed information than the borehole sampling and is used to evaluate Pu and Am contamination in the on-site area. The Phase I Remedial Investigation is used to evaluate the background concentration of radionuclides and the soil concentrations of the

other radionuclides. Table 3.1 presents the background concentration data. The In-Situ survey is presented in more detail in Appendix C.

Cesium-137 (Cs-137), tritium (H-3), and uranium (U-233,-234,-235, and -238) were also detected in the borehole sampling, albeit at near background concentrations and in only a few samples. Both surveys concluded that Cs-137 contamination is consistent with global fallout. The concentrations of tritium and uranium were negligible in the surficial material. Therefore, only plutonium and americium contamination in soil were evaluated.

3.3.2 Groundwater

Ground water sampling taken for the Phase I Remedial Investigation is used to evaluate the radionuclide contamination in groundwater in the on-site area. Because there are no sampling wells in the Remedy Acreage (off-site areas), no groundwater sampling data exists. However, no ground water contamination is expected since the ground water contamination plume at OU 2 does not extend to OU 3. Further characterization is necessary and will be done for the Phase II RFI/RI.

The Phase I borehole sampling program for OU2 concludes that radionuclide contamination is apparently limited to surficial soils. Only plutonium, americium, and uranium exceed background, albeit only slightly and in only a few samples. The data is inconclusive. In addition, the RESRAD leaching model indicates that neither plutonium nor americium could have leached into the ground water within the past 40 years. For these reasons plutonium, americium, and uranium were assumed not to be present initially in the ground water.

Table 3.1. Background Concentrations of Radionuclides

Radionuclide	Surficial Material (pCi/g)		Groundwater (pCi/L)	
	RF Alluvium	Colluvium	RF Alluvium	Colluvium*
U-233,-234	1.491	1.759	1.647	11
U-235	0.087	0.169	0.000	0.3
U-238	1.353	1.675	0.195	7.7
Sr-89,-90	0.768	0.776	0.552	0.1
Pu-239,-240	0.017	0.023	0.009	0
Am-241	0.018	NR	0.000	0
Cs-137	0.082	0.113	0.603	0.2
Tritium	0.410	0.299	309	100

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* - Maximum Detected Value

NR - Analyte Not Reported

Source: "Final Phase II RFI/RI Work Plan, Alluvial, Technical Memorandum 1, Operable Unit No. 2," EG&G Rocky Flats, 19 August 1991

4. ASSUMPTIONS AND DATA

Many assumptions are made with regard to this radiological assessment. They may be divided into three general categories. The first category consists of those parameters related to human activity or living patterns of the receptors. These parameters form the basis of the exposure scenario. The scenario is a prediction of future human activities by the receptors on each of the contaminated areas based on a reasonable comparison to the appropriate land use expected for that area once it is released to the public.

The second category involves assumptions regarding the geology and hydrology of RFP. Because the geology and hydrology are complex, they must be simplified to derive the parameters that are used in the RESRAD leaching/groundwater transport model. These simplifications are summed up in a hydrological model for each of the three contaminated areas.

The third category involves assumptions about the source. The assumptions involving the boundaries of the three areas for this assessment are discussed in Sect. 1.3. The initial concentrations of radionuclides in soil and all of the parameters directly related to the contaminated zone are discussed.

4.1 EXPOSURE SCENARIOS

Exposure scenarios describe patterns of human activity that can affect the release of radioactivity from the contaminated zone and the amount of exposure received at the exposure location. Thus, exposure scenarios used for establishing soil guidelines should correspond to actions, events, and processes that are either realistic for the location and/or will result in the largest exposure likely to occur to the receptors.

The parameters that are principally dependent upon scenarios are dietary and

nondietary ingestion parameters, the amount of time the receptor spends outdoors in the contaminated zone, the amount of time the receptor spends indoors in the contaminated zone (with partial shielding afforded by the building structure), irrigation methods and rates, and the mass loading of soil.

4.1.1 Family-Farm Scenario

A single scenario, the family farm (as specified in DOE/CH/8901), was considered for both OUs. This scenario assumes that a family of four moves onto the contaminated zone and constructs a farm. Further, the family is assumed to raise crops and livestock for consumption and to use groundwater as a source of drinking water by means of a well.

Members of the family can incur a radiation dose by (1) direct radiation from radionuclides in the soil, (2) inhalation of resuspended dust (if the contaminated area is exposed at the ground surface), (3) ingestion of food from crops grown in the contaminated soil, (4) ingestion of milk from livestock raised in the contaminated area, (5) ingestion of meat from livestock raised in the contaminated area, (6) ingestion of fish from a nearby pond contaminated by water percolating through the contaminated zone, and (7) ingestion of water from a well contaminated by water percolating through the contaminated zone (Yu, 1992).

The scenario assumes that half of the family's total plant food diet will be grown on the farm and the other half will be purchased at market. For each individual the land required to grow a year's supply of food is 50 m² for leafy and other aboveground vegetables, 200 m² for root vegetables and grains, and a somewhat larger area for fruit trees. Based on these figures, the RESRAD manual suggests approximately 1,000 m² (0.1 ha) is sufficient to grow half of the plant food consumed by the farm family.

The scenario also assumes that all of the family's total meat and milk diet will be obtained from the livestock raised on the farm. The land required to support livestock, including summer pasture and forage for winter use, is larger than that required to grow plant foods. Each pig requires a food supply from an area of about 2,000 m² (0.2 ha) and

each milk cow may require a forage supply from an area of 10,000 m² (1 ha) or more. Based on these figures, the RESRAD manual suggests approximately 20,000 m² (2 ha) is sufficient to raise enough livestock to supply meat and milk for a family of four. Since all three contaminated areas in OU 2 and OU 3 are significantly larger than 21,000 m² (2.1 ha), all of the plants, meat, and milk produced by the farm are considered to be contaminated. Thus, the area factor for ingestion, FA₃, is unity.

The RESRAD methodology considers the family-farm scenario to be a credible and bounding. Although the area surrounding the RFP is expected to become predominantly residential in the next 50 years, the family-farm scenario was chosen over a residential scenario because it is more conservative.

The family-farm scenario for OU 2 assumes that the family of four, described in the RESRAD manual, establishes a house, a 1,000 m² garden, and a 20,000 m² livestock pen in the center (maximum exposure to external gamma radiation) of the contaminated zone. The family-farm scenario for OU 3 is slightly different. OU 2 is located on land historically and currently owned by the DOE, and OU 3 is located on land that is neither. The scenario assumes that as a settlement to the 1975 lawsuit, DOE, instead of the city of Broomfield and Jefferson County, purchased the Remedy Acreage from the landowners. Under current circumstances, DOE Order 5400.5 does not apply to OU 3 because the land is not property of the U.S. DOE. As for OU 2, the scenario assumes the same farm family establishes a farm in the center of the OU 3 North and OU 3 South contaminated zones.

4.1.1.1 Family-Farm Scenario Parameters

Scenario-specific parameters used in the RESRAD computations for the family-farm scenario are listed in Tables 4.1 and 4.2. These parameters are discussed in the

Table 4.1. Specific Pathways Considered Under the Family-Farm Scenario.

Parameter	All Operable Units
<i>Specific Pathways</i>	
Pathway 1: External Gamma Radiation	Active
Pathway 2: Dust Inhalation	Active
Pathway 3: Plant Ingestion	Active
Pathway 4: Meat Ingestion	Active
Pathway 5: Milk Ingestion	Active
Pathway 6: Aquatic Foods	Active
Pathway 7: Drinking Water	Active
Pathway 8: Radon	Suppressed

Table 4.2. Scenario - Specific Parameters for the Family-farm scenario.

Parameter	All Operable Units		
	Low	Nominal or Default	High
<i>Ingestion - Dietary¹</i>			
Fruits, Vegetables, and Grain Consumption (kg/yr)	-	190	300
Leafy Vegetables Consumption (kg/yr)	-	30	45
Milk Consumption (L/yr)	92	110	200
Meat and Poultry Consumption (kg/yr)	-	95	110
Fish Consumption (kg/yr)	-	6.9	21
Other Seafood Consumption (kg/yr)	-	1.0	5.0
Soil Ingestion (g/yr)	-	36.5	43.8
Drinking Water Consumption (L/yr)	-	510	730
Fraction of Drinking Water from Site (dimensionless)	0.5	1.0	-
Fraction of Aquatic Food from Site (dimensionless)	-	0.5	1.0
<i>Ingestion - Nondietary²</i>			
Livestock fodder intake for meat (kg/d)	-	68	-
Livestock fodder intake for milk (kg/d)	-	55	-
Livestock water intake for meat (L/d)	-	50	-
Livestock water intake for milk (L/d)	-	160	-
Mass Loading for Foliar Deposition (g/m ³)	-	0.0001	-
Depth of Soil Mixing Layer (m)	-	0.15	-

Table 4.2. Scenario-Specific Parameters for the Family Farm Scenario (continued)

Parameter	All Operable Units		
	Low	Nominal or Default	High
<i>Ingestion - Nondietary (continued)</i>			
Depth of Roots (m)	-	0.9	-
Groundwater Fractional Usage:			
Drinking Water (dimensionless)	0.5	1.0	-
Livestock Water (dimensionless)	0.5	1.0	-
Irrigation (dimensionless)	0.5	1.0	-
<i>Miscellaneous</i>			
Irrigation mode	-	overhead	-
Occupancy Factor (dimensionless)	-	0.45	-
Occupancy and Shielding Factor (dimensionless)	-	0.60	-
Inhalation Rate (kg/yr)	-	8760	10,000

following three sections. Section 4.1.1.1 discusses dietary ingestion rates and other directly-related parameters. Section 4.1.1.2 discusses livestock ingestion rates and other parameters indirectly related to human ingestion. Section 4.1.1.3 discusses all of the other parameters that are determined by the scenario but are not related to human ingestion.

4.1.1.1 Dietary Ingestion Parameters

Dietary ingestion parameters consist of nine parameters used in RESRAD that are directly related to the human diet. Seven of these parameters are annual consumption rates and the other two are fractional usage (ratio of on-site to total consumption) parameters. Environmental Protection Agency (EPA) values are used wherever practical. For those parameters where EPA information is inadequate, Nuclear Regulatory Commission (NRC) values are used.

The fruits, vegetables, and grain consumption parameter is the annual rate of intake for fruits, non-leafy vegetables, and grain. EPA defines the average consumption of vegetables per person as 200 g/d (73 kg/yr), where 25% of the consumption is home-grown products. Total average daily individual fruit consumption is 140 g/d (51 kg/yr), where 28 g/d (10 kg/yr) is from homegrown products. EPA recommendations do not include information about grain product consumption. The NRC defines the average individual adult consumption of fruits, vegetables, and grains as 190 kg/yr and a worst case value 520 kg/yr (Yu, 1992b). The NRC consumption rates were selected because they included grain consumption. However, the maximum value of 520 kg/yr exceeds the input range for RESRAD. Instead, the maximum input value, 300 kg/yr, is used.

The leafy vegetables consumption parameter is the annual rate of intake for leafy vegetables such as lettuce and spinach. The NRC defines the adult consumption rate as

30 kg/yr for environmental dose analyses. The worst case value is assumed to be 45 kg/yr (50% increase) (Yu, 1992b).

The milk consumption parameter is the annual rate of intake of milk. The EPA estimates that the rate of intake for fresh milk varies from 254 g/d to 1,000 g/d per person, with an average rate of 305 g/d (110 L/yr). The RESRAD methodology assumes that all of the consumed milk is from cows raised on the farm and all of the milk is contaminated if the contaminated area is greater than or equal to 20,000 m². For all three contaminated areas, all of the milk consumed by the receptors is considered to be from cows raised in contaminated areas. The rate of intake is 110 L/yr with best and worst case values of 92 L/yr and 360 L/yr respectively (Yu, 1992b). However, the maximum value of 300 L/yr exceeds the input range for RESRAD. Instead, the maximum input value, 200 L/yr, is used.

The meat and poultry consumption parameter is the annual rate of intake of meat and poultry. The EPA suggests that the average consumption of beef is 100 g/d (36.5 kg/yr), where 44 g/d is from homegrown beef. For a reasonable worst case, the EPA suggests a consumption rate of 75 g/d (27 kg/yr). The NRC recommends that the average value for the consumption of meat and poultry is 95 kg/yr and recommends that the worst case value is 110 kg/yr (Yu, 1992b). The NRC recommended values were used for the family-farm scenario.

The fish consumption parameter is the annual rate of intake of fish, and the other seafood consumption parameter is the annual rate of intake of other seafood. EPA suggests 30 g/d (11 kg/yr) and 140 g/d (51 kg/yr) for the 50th and 90th percentile seafood consumption rates of fishermen. The NRC suggests the average individual adult fish consumption rate is 6.9 kg/yr and suggests the worst case value is 21 kg/yr. For other

aquatic food, the NRC suggests the average consumption rate is 1.0 kg/yr and suggests the worst case value is 5 kg/yr (Yu, 1992b). Surface water bodies located at the site will provide 50% of the consumption of fish and other aquatic food. The rest is purchased at market. Thus, the fraction of aquatic foods from site for the nominal and best case is 50%. However, the worst case assumes 100% of the aquatic diet is obtained on-site.

The soil ingestion parameter is the annual accidental ingestion rate of soil material or soil dust. EPA suggests 0.2 g/d for children (0 to 6 years old) and 0.1 g/d for adults (7+ years old). For an adult, the annual soil ingestion rate is 36.5 g/yr. EPA also suggests 43.8 g/yr for a 30-year residential scenario ($73 \text{ g/yr} \times 6 \text{ yr} + 36.5 \text{ g/yr} \times 24 \text{ yr}$) (yu, 1992b).

The drinking-water intake rate parameter is the annual amount of drinking water consumed by the receptor. EPA suggests the average adult drinking-water consumption rate is 1.4 L/d (510 L/yr) and the worst case rate is 2.0 L/d (730 L/yr) (Yu, 1992b). The fraction of drinking water from the site is assumed to be 100% for the nominal and worst case and 50% for the best case.

The fraction of drinking water from the site is assumed to be 1.0 (100%) for the nominal and worst-case scenario. For the best-case the fraction is assumed to be 0.5 (50%). The fraction of aquatic food from site is assumed to be 0.5 (50%) for the nominal and best-case. For the worst-case the fraction is assumed to be 1.0 (100%).

4.1.1.1.2 Non-dietary Ingestion Parameters

Non-dietary ingestion parameters consist of ten parameters used in RESRAD that are indirectly related to the human diet. Four of these parameters are annual fodder consumption rates for livestock, three describe the fraction of the water used for drinking water, livestock water, and irrigation drawn from groundwater, and the other three are

related to the uptake of radionuclides by plants and crops (Yu, 1992b).

Livestock fodder and water intake rates for beef cattle and milk cows used in the assessment are the suggested values in the RESRAD manual. The fodder intake rate for beef cattle is 68 kilograms per day and the fodder intake rate for milk cows is 55 kilograms per day. The water intake rate for beef cattle is 50 liters per day. The water intake rate for milk cows is 14 gallons per day plus 1 gallon for every 3 pounds of milk produced. Assuming a production rate of 10 gallons per day, the water intake rate for milk cows is about 160 liters per day (Yu, 1992b).

The drinking water, livestock water, and irrigation groundwater fractional usage parameter describes the fraction of the total amount of water used for those three uses that comes from groundwater (potentially contaminated). To be conservative, it is assumed that all of the water used for drinking water, livestock water, and irrigation comes from the groundwater (Yu, 1992b).

The mass loading factor for foliar deposition and the depth of the soil mixing layer are both assumed to be the suggested RESRAD default values of 0.0001 g/m^3 and 0.15 m. The depth of roots varies for different plants. For beets, carrots, lettuce, etc. it is usually no more than 0.3 m, and for fruit trees it is usually no more than 2 to 3 m. Most plant roots are less than 1 m. The RESRAD manual default value is 0.9 m, and it is used for this assessment (Yu, 1992b).

4.1.1.1.3 Miscellaneous Parameters

Miscellaneous parameters consist of seven parameters used in RESRAD that are determined by the scenario but are not related to human ingestion. Irrigation rate and mode influence the environmental transport of radionuclides for the ingestion pathways. The occupancy and shielding factor influences the exposure to direct gamma radiation.

The last four parameters are all related to the environmental transport of radionuclides for inhalation exposure.

Irrigation of plants and crops in the contaminated areas is assumed to be by an overhead method. The irrigation rate is discussed in Sect. 3.2.

The occupancy factor for inhalation is 0.45. This factor is based on the assumption that the receptor spends 50% of the time indoors and on-site (where the dust level is 40% of that outdoors), 25% of the time outdoors and on-site (where the dust level is 100%), and 25% of the time off-site (where the dust level is 0%) (Yu, 1992).

The occupancy and shielding factor for external gamma radiation is 0.60, based on the assumption that the receptor spends 50% of the time indoors and on-site (where the radiation exposure level is 70% of that outdoors), 25% of the time outdoors and on-site (where the radiation exposure is 100%), and 25% of the time off-site (where the radiation exposure is 0%) (Yu, 1992).

The inhalation rate parameter is the volume of air inhaled by the receptor annually. This rate varies with activity level, age, weight, sex, and general physical condition. The *Draft Data Collection Handbook for Establishing Residual Radioactive Material Guidelines with RESRAD* recommends that for an individual performing outdoor activities a reasonable inhalation rate is 1.4 m³/h with a worst-case value of 3.0 m³/h. The manual also recommends that for an individual performing indoor activities a reasonable inhalation rate is 0.63 m³/h with a worst-case value of 0.89 m³/h. As for the occupancy factor the receptor is assumed to spend 50% of the time indoors and the rest outdoors. A reasonable inhalation rate for the receptor in the family-farm scenario is 1.0 m³/h (8760 m³/yr), assuming 50% of the time at 1.4 m³/h and 50% of the time at 0.63 m³/h, with a worst case value of 1.9 m³/h (16,600 m³/yr), assuming 50% of the time at 3.0 m³/h and

50% of the time at 0.89 m³/h. However, the maximum value of 16,600 m³/yr exceeds the input range for RESRAD. Instead, the maximum input value, 10,000 m³/yr, is used.

The soil mass loading factor is also affected by the activity in the contaminated areas as determined by the scenario. However, this parameter is discussed in the Source Characterization.

4.2 GEOLOGY AND HYDROLOGY

Because contaminants in the soil leach into groundwater used by the farmer/receptor, hydrological parameters must be determined for use in RESRAD calculations. The geology and hydrology of the RFP area is complex and the parameters vary considerably; therefore, several assumptions and simplifications have been made. These assumptions and simplifications are collectively referred to as hydrological models.

4.2.1 Hydrological Models

4.2.1.1 On-Site Contaminated Area

Hydrological parameters for the on-site contaminated area are presented in Table 4.3 with their respective values. Sections 4.2.1.1.1, 4.2.1.1.2, and 4.2.1.1.3 describe these parameters and how their respective values are calculated or obtained.

4.2.1.1.1 Contaminated, Vadose, and Saturated Zone Strata Thicknesses

The thicknesses of the contaminated, vadose, and saturated zones are shown in Fig. 4.1. The on-site surficial material consists predominantly of Rocky Flats Alluvium. The depth to the Arapahoe Bedrock varies from about 44 ft (13.4 m) along the western edge of OU 2 to virtually nothing where the Arapahoe Bedrock outcrops, according to well-construction data presented in the *Final Phase II RFI/RI Work Plan (Alluvium), Technical Memorandum 1, 903 Pad, Mound, East Trenches Areas (Operable Unit No. 2)*. The average depth is approximately 17.5 ft (5.33 m).

Table 4.3. On-Site Area Hydrological Parameters

Parameters	Parameter Value		
	Low	Nominal	High
<i>Contaminated Zone Hydrological Parameters</i>			
Density of Contaminated Zone (g/cm^3)	-	1.44	-
Contaminated Zone Total Porosity (dimensionless)	0.24	0.33	0.46
Contaminated Zone Effective Porosity (dimensionless)	0.13	0.25	0.43
Contaminated Zone Hydraulic Conductivity (m/yr)	0.32	19	32
Contaminated Zone b Parameter (dimensionless)	-	4.9	-
Evapotranspiration Coefficient (dimensionless)	0.70	0.80	0.90
Precipitation (m/yr)	-	0.38	-
Runoff Coefficient (dimensionless)	-	0.2	-
Watershed Area for Nearby Stream or Pond (m^2)	-	37,555,000	-

Table 4.3. On-Site Area Hydrological Parameters (continued)

Parameters	Parameter Value		
	Low	Nominal	High
<i>Vadose (Uncontaminated and Unsaturated) Zone Hydraulic Parameters</i>			
Thickness (m)	-	2.90	-
Soil Density (g/cm ³)	-	1.44	-
Total Porosity (dimensionless)	0.24	0.33	0.46
Effective Porosity (dimensionless)	0.13	0.25	0.43
Soil-Specific b Parameter (dimensionless)	-	4.9	-
Hydraulic Conductivity (m/yr)	0.32	19	32
<i>Saturated Zone Hydraulic Parameters</i>			
Density of Saturated Zone (g/cm ³)	-	1.44	-
Saturated Zone Total Porosity (dimensionless)	0.24	0.33	0.46
Saturated Zone Effective Porosity (dimensionless)	0.13	0.25	0.43
Saturated Zone Hydraulic Conductivity (m/yr)	0.32	19	32
Saturated Zone Hydraulic Gradient (dimensionless)	-	0.02	-
Saturated Zone b Parameter (dimensionless)	-	4.9	-
Water Table Drop Rate (m)	-	0	-

Table 4.3. On-Site Area Hydrological Parameters (continued)

Parameters	Parameter Value		
	Low	Nominal	High
<i>Saturated Zone Hydraulic Parameters (continued)</i>			
Well Pump Intake Depth (m)	0.5	1.78	-
<i>Model for Water Transport Parameters</i>			
Nondispersion or Mass-Balance Model	Nondispersion	Nondispersion	Nondispersion
Individual's Use of Groundwater	N/A	N/A	N/A
<i>Distribution Coefficients (cm³/g)</i>			
Americium	20	200	2000
Plutonium	200	550	2000

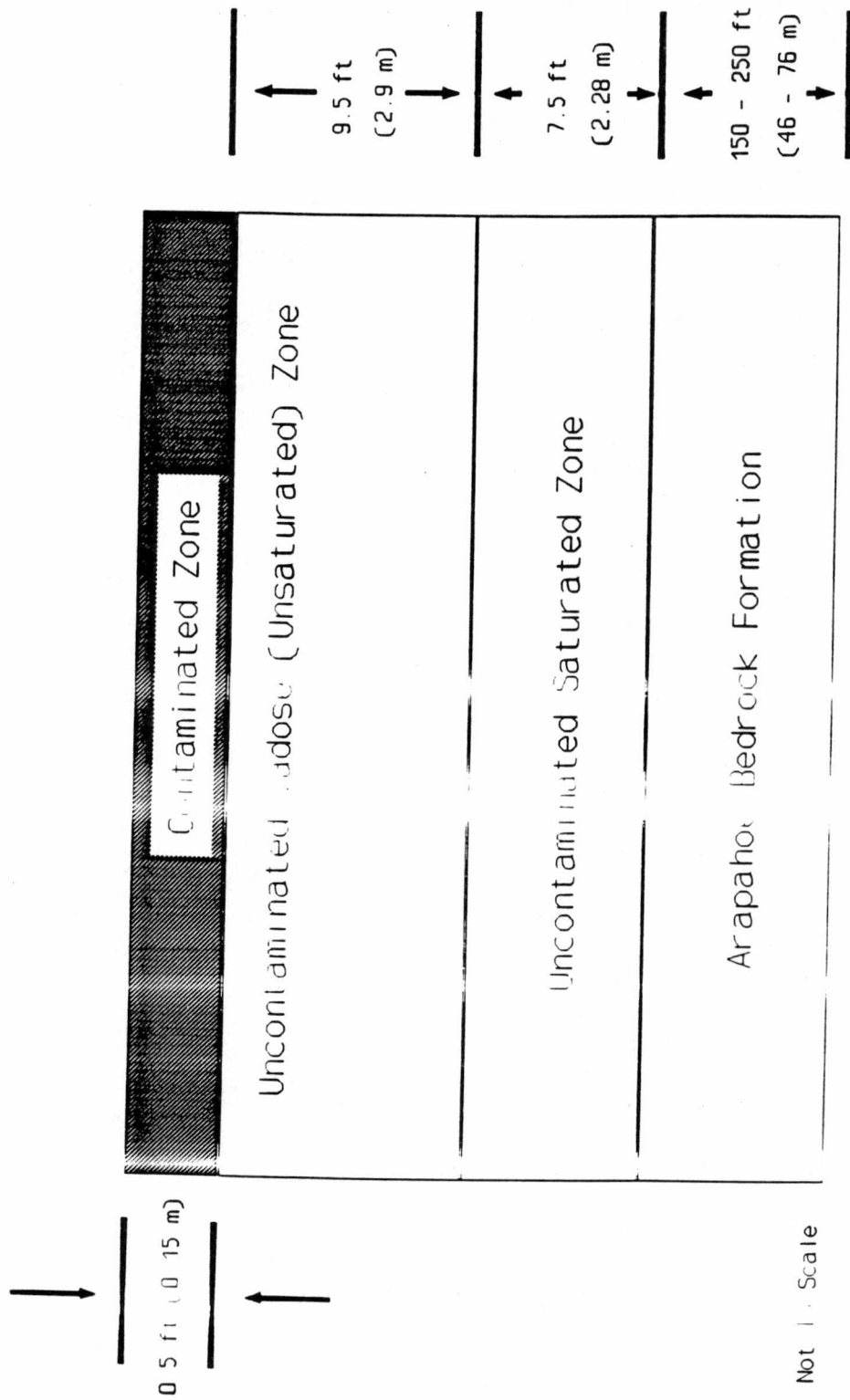


Fig. 4.1. Hydrological Model for On-Site Area

A potentiometric surface map constructed from data collected in April 1988 and presented also in the Final Phase II RFI/RI Work Plan (Alluvium), Technical Memorandum 1, 903 Pad, Mound, East Trenches Areas (Operable Unit No. 2) indicates that the water table is approximately 10 ft below the surface. The water table is highest during the spring months of May and June. During the late summer and fall, the water table generally declines, with some wells becoming dry. The water table is assumed to be in hydrological steady-state at the spring and early summer levels for all three areas. Thus, the Water Table Drop Rate is 0 m/yr.

The thickness of the saturated zone is approximately 2.28 m, the depth to the bedrock (5.33 m) minus the depth to the water table (3.05 m). The remaining 3.05 m consists of the thickness of the contaminated zone and the thickness of the vadose zone. The contaminated zone thickness, 0.15 m, is discussed in Sect. 3.3.1. The vadose zone thickness is approximately 2.9 m.

4.2.1.1.2 Bulk Soil Density, Total Porosity, Effective Porosity, Soil-Specific b Parameter, and Hydraulic Conductivity

The three strata (the contaminated zone, the vadose zone, and the saturated zone) are assumed to be relatively homogenous. Thus the hydraulic conductivity, total porosity, effective porosity, and bulk soil density are the same for each of the three zones.

Bulk soil density is the ratio of the mass of the solid phase of the soil (dry soil) to its total volume (solid and pore volumes together). Rocky Flats Alluvium is a gravelly pediment cover composed of poorly sorted, angular to rounded, coarse gravel, sands, and gravelly clays. The Soil Conservation Service (SCS) describes the top soil as a sandy loam. The typical bulk soil density for sandy loam is 1.44 g/cm^3 (Yu, 1992b). This bulk soil density is assumed to be the same throughout the surficial material.

Total porosity of a porous medium is the ratio of the pore volume to the total

volume of the medium. The typical total porosity for Rocky Flats Alluvium ranges from 0.24 (coarse gravel) to 0.46 (coarse sand) with a mean value of 0.33 (Yu, 1992b).

Effective porosity of a porous medium is the ratio of the part of the pore volume where water may freely circulate to the total volume. It is always lower than the total porosity. The typical effective porosity for Rocky Flats Alluvium ranges from 0.13 (coarse gravel) to 0.43 (coarse sand) with a mean value of 0.25 (Yu, 1992b).

"The soil-specific b parameter is an empirical and dimensionless parameter that is used to evaluate the saturation ratio (or the volumetric water saturation), R_s , of the soil, according to a soil characteristic function called the conductivity function (i.e., the relationship between the unsaturated hydraulic conductivity, k , and the saturation ratio, R_s). The b parameter was obtained from Table 13.1 of the *Draft Data Collection Handbook for Establishing Residual Radioactive Material Guidelines with RESRAD*. The soil-specific exponential b parameter for the soil located in the on-site area is 7.62.

The hydraulic conductivity of a soil is a measure of that soil's ability to transmit water when subjected to a hydraulic gradient. It is defined by Darcy's law, for one-dimensional vertical flow, which states,

$$U = -K \frac{dh}{dz} \quad (4.1)$$

where,

- U = Darcy's velocity (average velocity of water through a geometric cross-sectional area within the soil)
- h = hydraulic head
- z = vertical distance in soil
- K = coefficient of proportionality; also referred to as the hydraulic conductivity.

Thus, the hydraulic conductivity is essentially the ratio of Darcy's velocity to the applied hydraulic gradient. The hydraulic conductivity in the surficial material around the RFP is highly variable. This is easily explained when one considers that most of the surficial

material is poorly sorted and nonuniform. The *Draft Rocky Flats Surface Water Management Plan* gives a range of 10^{-6} to 10^{-8} m/s (32 to 0.32 m/yr) for the hydrological conductivity of the unconsolidated surficial deposits with a representative conductivity of roughly 6×10^{-7} m/s (19 m/yr). The unconsolidated surficial deposits include Rocky Flats Alluvium, colluvium, and Valley Fill Alluvium, which are all hydraulically connected. All three contaminated areas are assumed to have this hydraulic conductivity. The hydraulic conductivity is also assumed to be the same for the contaminated, vadose, and saturated zones.

4.2.1.1.3 Miscellaneous Parameters Related to the Hydrology

Evapotranspiration is the process where water changes from a liquid to a gaseous phase and is transferred to the atmosphere during a fixed period of time. It represents the combination of two separate processes, evaporation and transpiration. Evaporation involves the direct transfer of water vapor from the ground to the atmosphere through plants and their foliage. "The evapotranspiration coefficient, C_e , is the ratio of the total volume of water leaving the ground due to evapotranspiration, ET_r , to the total volume of water available within the root zone of the soil $((1-C_r)P_r + IR_r)$ during a fixed period of time" (Yu, 1992b). The evapotranspiration coefficient is assumed to range from 0.70 to 0.90 with an average of 0.80 for all of the areas (Yu, 1992b).

The precipitation rate is the average volume of water in the form of rain, sleet, snow, or hail that falls per unit area and unit time. The *Final Phase II RFI/RI Work Plan (Alluvium)*, *Technical Memorandum 1*, 903 Pad, Mound, East Trenches Areas (Operable Unit No. 2) and the *Final RFI/RI Work Plan for Operable Unit No. 3* both give an average annual precipitation rate of 15 in/yr (0.38 m/yr).

The average annual runoff coefficient is the fraction of the average annual

precipitation that does not infiltrate into the soil and is not transferred back to the atmosphere through evapotranspiration. This fraction represents the precipitation that becomes surface water and ends up in the intermittent streams. The average annual runoff coefficient for all three contaminated areas is assumed to be that for rolling land, 0.2, given in the *Draft Data Collection Handbook for Establishing Residual Radioactive Material Guidelines with RESRAD*. It is assumed to vary by 0.1 for a maximum value of 0.3 and a minimum value of 0.1.

The irrigation rate is the average volume of water that is artificially added to the soil at the site, per unit surface area and unit time, to compensate for a shortage of required precipitation. The necessary irrigation rate, IR_r , can be estimated by the following equation,

$$IR_r = \frac{ET_r}{C_e} - (1 - C_r)P_r \quad (4.2)$$

where,

- ET_r = potential evapotranspiration rate (m/yr)
- C_e = irrigation efficiency (dimensionless)
- C_r = runoff coefficient (dimensionless)
- P_r = precipitation rate (m/yr) (Yu, 1992b)

Irrigation efficiency is the ratio of the volume of water used consumptively to the total volume applied to the field. While irrigation efficiencies of 80% to 90% may be achieved with proper water management, many irrigation projects have an efficiency of less than 50% (Yu, 1992b). Irrigation efficiencies for the three contaminated areas are assumed to be 50%. The calculated irrigation rate ranges from 0.72 m/yr to 0.92 m/yr with an average value of 0.82 m/yr.

The watershed area evaluates the dilution factor for the contamination of on-site streams or ponds as the water is mixed from the inflow of water from the contaminated

aquifer. It is the surface drainage area of the region encompassing the contaminated site. The area was calculated from Fig. III-13 of the *Draft Rocky Flats Surface Water Management Plan*. This figure illustrates the Rocky Flats drainage basins that have an area of approximately 37,555,000 m².

"The hydraulic gradient is the change in hydraulic head per unit of distance of the groundwater flow in a given direction. For an unconfined aquifer like the one at the three contaminated areas, the hydraulic gradient of groundwater flow is approximately the slope of the water table. The *Final Phase II RFI/RI Work Plan (Alluvium), Technical Memorandum 1, 903 Pad, Mound, East Trenches Areas (Operable Unit No. 2)* gives a gradient of 0.02 around the RFP.

The water table drop rate is the rate at which the water table drops due to unusually high consumptive uses. The water table is assumed to be hydraulically stable. Thus, the drop rate is 0 m/yr.

The well pump intake depth is the depth at which water is taken from the aquifer. For the on-site and northern off-site areas, the water is assumed to be withdrawn 0.5 m above the bottom of the aquifer. The well pump intake depths for the on-site and northern off-site areas are 1.78 and 2.85 m, respectively. Because the saturated zone for the southern off-site area is so shallow, the depth is assumed to be 0.25 m above the bottom of the aquifer. Thus, the well pump intake depth for the southern off-site area is 0.32 m. For a worst-case scenario, the water is assumed to be withdrawn 0.5 m below the top of the aquifer for the on-site and northern off-site areas and 0.25 m below the top of the aquifer for the southern off-site area.

A sorption-desorption ion-exchange leaching model is used to model leaching by infiltrating water (precipitation and irrigation). The extent to which a radionuclide is

absorbed is commonly measured by a parameter known as the distribution coefficient, K_d . The distribution coefficient is the radionuclide equilibrium concentration ratio of the mass of solute absorbed on the solids per unit of dry mass of the soil, S , to the solute concentration in the liquids, C . This parameter represents the partition of the solute in the soil matrix and water as illustrated by the following equation,

$$S = K_d C$$

The dimensions of the distribution coefficient are $\text{cm}^3 / \text{gram}$.

4.2.1.2 Northern Off-Site Contaminated Area

Hydrological parameters for the northern off-site contaminated area are presented in Table 4.4 with their respective values. Sections 4.2.1.2.1, 4.2.1.2.2, and 4.2.1.2.3 describe these parameters and how their respective values are calculated or obtained.

4.2.1.2.1 Contaminated, Vadose, and Saturated Zone Strata Thicknesses

Neither the northern or southern off-site areas have any dedicated groundwater monitoring wells, and hydrological data for these two sites are limited. The northern off-site area consists of mostly Verdos Alluvium and colluvium with some small deposits of Slocum. The *Rocky Flats Plant Geological Characterization Report* gives a thickness of 15 ft (4.6 m) to 35 ft (10.7 m) for Verdos Alluvium. The *Draft Rocky Flats Plant Surface Water Management Plan* gives a maximum thickness of 3 ft (0.92 m) for the colluvium. Drilling and filing records of numerous privately-owned water wells held by the Colorado Division of Water Resources indicate that the off-site thickness of surficial deposits range from 15 to 50 ft (4.6 to 15 m) and average approximately 25 ft (7.6 m) near the Remedy Acreage. Drinking water wells used by the receptors in the northern off-site area are assumed to be located in Verdos Alluvium, and the thickness is assumed to be 25 ft (7.6 m).

Table 4.4. Northern Off-Site Area Hydrological Parameters

Parameters	Parameter Value		
	Low	Nominal	High
<i>Contaminated Zone Hydrological Parameters</i>			
Density of Contaminated Zone (g/cm^3)	-	1.28	-
Contaminated Zone Total Porosity (dimensionless)	0.24	0.33	0.46
Contaminated Zone Effective Porosity (dimensionless)	0.13	0.25	0.43
Contaminated Zone Hydraulic Conductivity (m/yr)	0.32	19	32
Contaminated Zone b Parameter (dimensionless)	-	8.52	-
Evapotranspiration Coefficient (dimensionless)			0.75
Precipitation (m/yr)	-	0.75	-
Runoff Coefficient (dimensionless)	0.1	0.2	0.3
Watershed Area for Nearby Stream or Pond (m^2)	-	37,555,000	-

Table 4.4. Northern Off-Site Area Hydrological Parameters (continued)

Parameters	Parameter Value		
	Low	Nominal	High
<i>Vadose (Uncontaminated and Unsaturated) Zone Hydraulic Parameters</i>			
Thickness (m)	-	4.1	-
Soil Density (g/cm ³)	-	1.28	-
Total Porosity (dimensionless)	0.24	0.33	0.46
Effective Porosity (dimensionless)	0.13	0.25	0.43
Soil-Specific b Parameter (dimensionless)	-	8.52	-
Hydraulic Conductivity (m/yr)	0.32	19	32
<i>Saturated Zone Hydraulic Parameters</i>			
Density of Saturated Zone (g/cm ³)	-	1.28	-
Saturated Zone Total Porosity (dimensionless)	0.24	0.33	0.46
Saturated Zone Effective Porosity (dimensionless)	0.13	0.25	0.43
Saturated Zone Hydraulic Conductivity (m/yr)	0.32	19	32
Saturated Zone Hydraulic Gradient (dimensionless)	-	0.02	-
Saturated Zone b Parameter (dimensionless)	-	5.82	-

Table 4.4. Northern Off-Site Area Hydrological Parameters (continued)

Parameters	Parameter Value		
	Low	Nominal	High
<i>Saturated Zone Hydraulic Parameters (continued)</i>			
Water Table Drop Rate (m)	-	0	-
Well Pump Intake Depth (m)	0.5	2.85	-
<i>Model for Water Transport Parameters</i>			
Nondispersion or Mass-Balance Model	Nondispersion	Nondispersion	Nondispersion
Individual's Use of Groundwater	N/A	N/A	N/A
<i>Distribution Coefficients (cm³/g)</i>			
Americium	20	200	2000
Plutonium	200	550	2000

The vadose and the saturated-zone thicknesses are calculated by assuming that the ratio for each of these two zones to the uncontaminated zone thickness (total surficial thickness minus the contaminated zone thickness) is the same as that for the on-site area. Thus, the thicknesses of the vadose and saturated zones are 4.1 m (13.5 ft) and 3.35 m (11.0 ft) respectively. The three zones for the northern off-site area are described in Fig. 4.2.

4.2.1.2.2 Bulk Soil Density, Total Porosity, Effective Porosity, Soil-Specific b Parameter, and Hydraulic Conductivity

The three zones, as previously described for the on-site contaminated area, are also assumed to be relatively homogenous. The bulk soil density, total porosity, effective porosity, and hydraulic conductivity are the same for each of the three zones.

Verdos and Slocum Alluviums are also gravelly pediment covers. Verdus Alluvium is composed of brown, well-stratified, coarse gravel and coarse sand. Slocum Alluvium is composed of reddish-brown, well-stratified, clayey, coarse gravel and coarse sand. Colluvium, located topographically below Verdus, Slocum, and Rocky Flats Alluviums, is the product of erosional processes. It is comprised of a mixture of soil, bedrock fragments, gravel, and sand.

The typical bulk soil density for the surficial material in the northern off-site area is 1.28 g/cm^3 . The typical total porosity ranges from 0.24 (coarse gravel) to 0.46 (coarse sand) with an mean value of 0.33, and the typical effective porosity ranges from 0.13 (coarse gravel) to 0.43 (coarse sand) with a mean value of 0.25. The soil-specific exponential b parameter for the soil located in the on-site area is 8.52. The hydraulic conductivity is assumed to be that described for the on-site contaminated area.

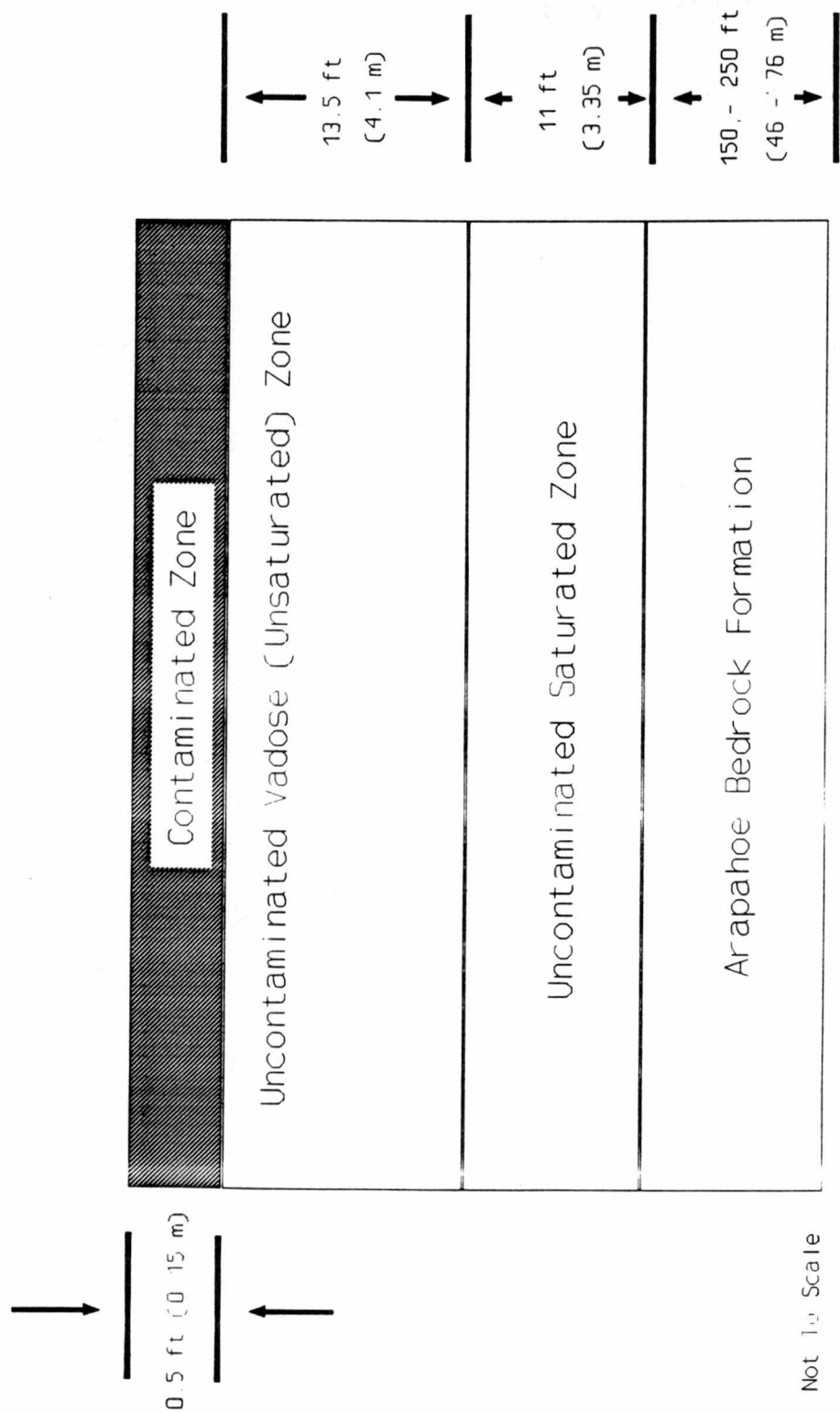


Figure 4.2. Hydrological Model for the Northern Off-Site Area

4.2.1.2.3 Miscellaneous Parameters Related to the Hydrology

The erosion rate, evapotranspiration coefficient, average annual precipitation rate, average annual runoff coefficient, and irrigation rate are considered to be the same for the three contaminated areas. Refer to Sect. 3.2.1.1.3 for a description of these parameters.

4.2.1.3 Southern Off-Site Contaminated Area

Hydrological parameters for the southern off-site contaminated area are presented in Table 4.5 with their respective values. Sections 4.2.1.3.1, 4.2.1.3.2, and 4.2.1.3.3 describe these parameters and how their respective values are calculated or obtained.

4.2.1.3.1 Contaminated, Vadose, and Saturated Zone Strata Thicknesses

As previously stated, neither the northern or southern off-site areas have any dedicated groundwater monitoring wells, and hydrological data for these two sites are limited. The contaminated zone for the southern off-site area is described in Fig. 4.3. This area consists of mostly shallow colluvium and Valley Fill Alluvium. The depth to the bedrock in the southern off-site area is much more shallow than that of the northern off-site area. The maximum thickness for colluvium is 2 to 3 ft (0.6 to 0.9 m), and the maximum thickness for the Valley Fill Alluvium is 10 ft (3.048 m) (EG&G, 1991a). For the purposes of deriving the vadose and saturated-zone thicknesses, the average thickness of the colluvium is assumed to be 2 ft (0.6 m) and the average thickness of the Valley Fill Alluvium is assumed to be 7.5 ft (2.3 m). The depth to the bedrock is assumed to be the average of these two values, 4.75 ft (1.45 m).

The vadose and the saturated-zone thicknesses, as in the previous example, are calculated by assuming that the ratio for each of these two zones to the uncontaminated zone thickness (total surficial thickness minus the contaminated zone thickness) is the same as that for the on-site area. Thus, the thicknesses of the vadose and saturated zones

Table 4.5. Southern Off-Site Area Hydrological Parameters

Parameters	Parameter Value		
	Low	Nominal	High
<i>Contaminated Zone Hydrological Parameters</i>			
Density of Contaminated Zone (g/cm^3)	N/A	1.28	N/A
Contaminated Zone Total Porosity (dimensionless)	0.34	0.43	0.54
Contaminated Zone Effective Porosity (dimensionless)	0.01	0.13	0.29
Contaminated Zone Hydraulic Conductivity (m/yr)	0.32	19	32
Contaminated Zone b Parameter (dimensionless)	-	10.4	-
Evapotranspiration Coefficient (dimensionless)	0.7	0.8	0.9
Precipitation (m/yr)	-	0.38	-
Runoff Coefficient (dimensionless)	0.1	0.2	0.3
Watershed Area for Nearby Stream or Pond (m^2)	-	37,555,000	-

Table 4.5. Southern Off-Site Area Hydrological Parameters (continued)

Parameters	Parameter Value		
	Low	Nominal	High
<i>Vadose (Uncontaminated and Unsaturated) Zone Hydraulic Parameters</i>			
Thickness (m)	-	0.73	-
Soil Density (g/cm ³)	-	1.28	-
Total Porosity (dimensionless)	0.34	0.43	0.54
Effective Porosity (dimensionless)	0.01	0.13	0.29
Soil-Specific b Parameter (dimensionless)	-	10.4	-
Hydraulic Conductivity (m/yr)	0.32	19	32
<i>Saturated Zone Hydraulic Parameters</i>			
Density of Saturated Zone (g/cm ³)	-	1.28	-
Saturated Zone Total Porosity (dimensionless)	0.34	0.43	0.54
Saturated Zone Effective Porosity (dimensionless)	0.01	0.13	0.29
Saturated Zone Hydraulic Conductivity (m/yr)	0.32	19	32
Saturated Zone Hydraulic Gradient (dimensionless)	-	0.02	-
Saturated Zone b Parameter (dimensionless)	-	5.82	-
Water Table Drop Rate (m)	-	0	-

Table 4.5. Southern Off-Site Area Hydrological Parameters (continued)

Parameters	Parameter Value		
	Low	Nominal	High
<i>Saturated Zone Hydraulic Parameters (continued)</i>			
Water Table Drop Rate (m)	-	0	-
Well Pump Intake Depth (m)	0.25	0.32	-
<i>Model for Water Transport Parameters</i>			
Nondispersion or Mass-Balance Model	Nondispersion	Nondispersion	Nondispersion
Individual's Use of Groundwater	N/A	N/A	N/A
<i>Distribution Coefficients (cm³/g)</i>			
Americium	20	200	2000
Plutonium	200	550	2000

are 0.73 m (2.4 ft) and 0.57 m (1.9 ft) respectively. The contaminated zone thickness, assumed to be the same for all three areas, is 0.15 m. The three zone thicknesses for the southern off-site area are described in Fig. 4.3.

4.2.1.3.2 Bulk Soil Density, Total Porosity, Effective Porosity, Soil-Specific b Parameter, and Hydraulic Conductivity

The three zones, as previously described for the on-site contaminated area, are also assumed to be relatively homogenous. The bulk soil density, total porosity, effective porosity, and hydraulic conductivity are the same for each of the three zones.

Valley Fill Alluvium is represented by poor- to well-graded mixtures of reworked Rocky Flats Alluvium, colluvium, and weathered bedrock with a dominant texture of silty clay and clayey silt with some gravel and sand. A typical bulk soil density for this type of material is 1.28 g/cm³. A typical total porosity ranges from 0.34 to 0.54, with a mean value of 0.43; a typical effective porosity ranges from 0.01 to 0.29 with a mean value of 0.13. The soil-specific exponential b parameter for the soil located in the on-site area is 10.4. The hydraulic conductivity is assumed to be the same as that described for the on-site contaminated area.

4.2.1.3.3 Miscellaneous Parameters Related to the Hydrology

The erosion rate, evapotranspiration coefficient, average annual precipitation rate, average annual runoff coefficient, and irrigation rate are considered to be the same for the three contaminated areas. Refer to Sect. 4.2.1.1.3 for a description of these parameters.

4.3 SOURCE CHARACTERIZATION

To determine the committed effective dose equivalent to a receptor from direct gamma, inhalation, or ingestion exposure, the source must be characterized. Section 3.3.1 will discuss each of the source parameters. Radionuclide concentrations are discussed

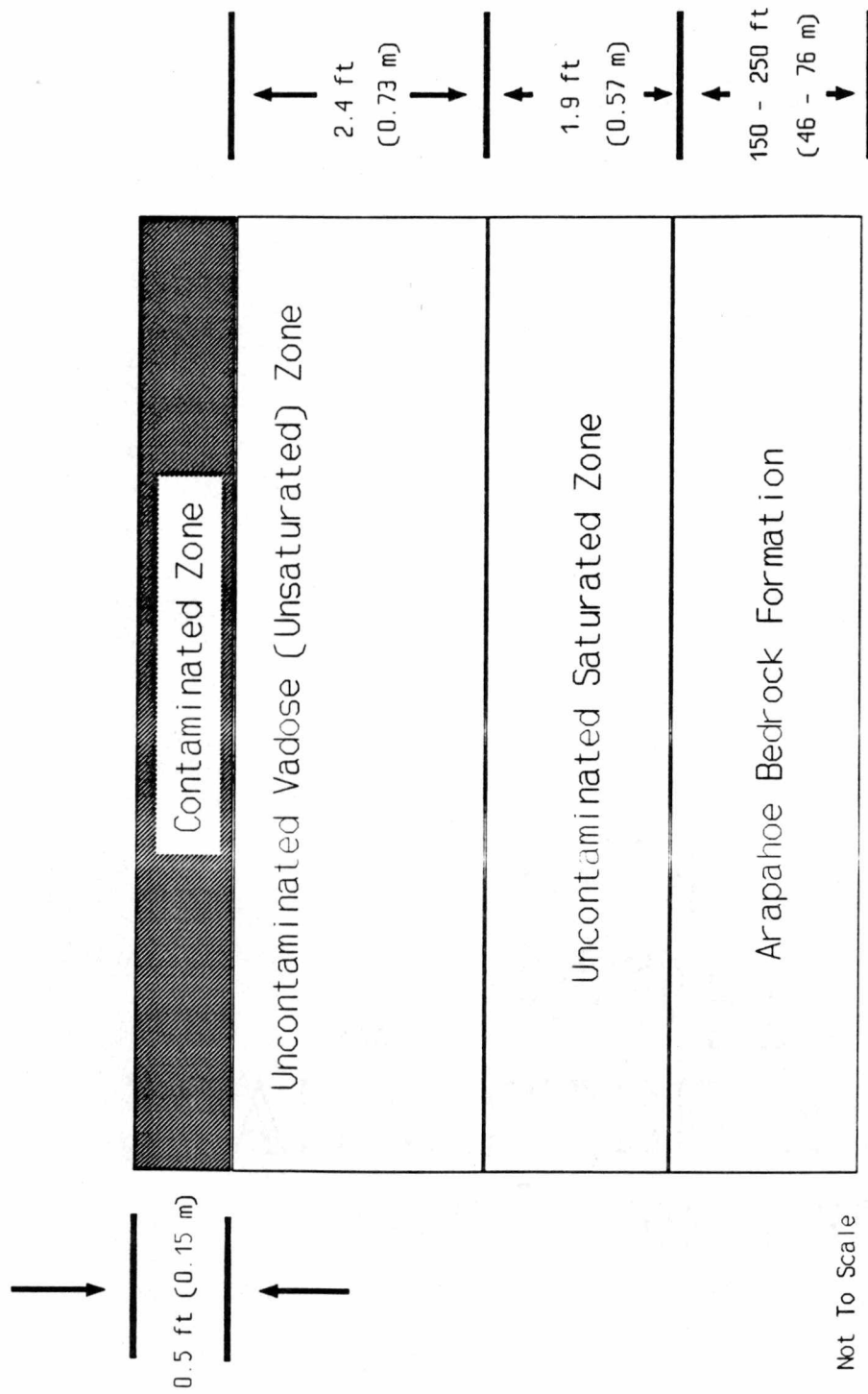


Figure 4.3. Hydrological Model for the Southern Off-Site Area

separately in Sect. 4.3.2. Information regarding the source characterization was obtained primarily from work plans, especially the *Phase II RFI/RI Work Plan (Alluvial)*, the *Phase II RFI/RI Work Plan (Bedrock) for OU 2*, and the *Final Draft Work Plan for OU 3*. Survey and environmental reports, especially the *1989 Aerial Radiological Survey* and the *1990 In Situ Survey*, were also used. Some parameters were estimated using guidelines outlined in the Draft Data Collection Handbook for RESRAD. The source parameters for the on-site, northern off-site, and southern off-site areas are listed in Tables 4.6, 4.7, and 4.8, respectively.

4.3.1 DESCRIPTION OF PARAMETERS

Twelve parameters in the RESRAD model describe the source, and some of them are also closely related to the hydrological parameters. Two of these parameters, the initial soil and water concentration of the principal radionuclides, are discussed in Sect. 4.3.2.

The location and dimensions of the on-site and two off-site contaminated areas are discussed in Sect. 1.3. The boundaries of the on-site area form a rectangle approximately 1,570 m by 605 m with an area of approximately 950,000 m². The northern area as shown in Fig. 1.3 is irregular. It has an area of approximately 1,005,000 m². The southern off-site area boundaries, also shown in Fig. 1.3, form a rectangle approximately 530 m by 423 m with an area of approximately 242,000 m². All three contaminated zones are defined as areas where the concentration of plutonium (all isotopes) in soil exceeds the Colorado Department of Health's special soil guideline of 0.9 pCi/g.

The contaminated zone thickness for all three contaminated areas was calculated by assuming that the radionuclide concentration with respect to depth has an exponential

Table 4.6. Source Characterization Parameters for the On-Site Area

Parameter	Parameters Values		
	Low	Nominal	High
Thickness of Cover Material (m)	0	0	0
Density of Cover Material (g/m ³)	N/A	N/A	N/A
Cover Erosion Rate (m/yr)	N/A	N/A	N/A
Contaminated Zone Area (m ²)	-	951,000	-
Thickness of the Contaminated Zone (m)	-	0.15	-
Density of Contaminated Zone (g/cm ³)	-	1.44	-
Contaminated Zone Erosion Rate (m/yr)	0.00015	0.00031	0.00047
Length Parallel to the Aquifer Flow (m)	-	1600	-
Dilution Length (m)	0.03	3	250
Soil Mass Loading (g/m ³)	0.0000209	0.0000591	0.0002
Time Since Material Placement (yr)	-	0	-
Shape Factor (dimensionless)	1.0	1.0	1.0

Table 4.7. Source Characterization Parameters for the Northern Off-Site Area

Parameter	Parameters Values		
	Low	Nominal	High
Thickness of Cover Material (m)	-	0	-
Density of Cover Material (g/m ³)	N/A	N/A	N/A
Cover Erosion Rate (m/yr)	N/A	N/A	N/A
Contaminated Zone Area (m ²)	-	1,005,000	-
Thickness of the Contaminated Zone (m)	-	0.15	-
Density of Contaminated Zone (g/cm ³)	-	1.28	-
Contaminated Zone Erosion Rate (m/yr)	0.00017	0.00034	0.00052
Length Parallel to the Aquifer Flow (m)	-	1540	-
Dilution Length (m)	0.03	3	250
Soil Mass Loading (g/m ³)	0.0000209	0.0000591	0.0002
Time Since Material Placement (yr)	-	0	-
Shape Factor (dimensionless)	-	1.0	-

Table 4.8. Source Characterization Parameters for the Southern Off-Site Area

Parameter	Parameters Values		
	Low	Nominal	High
Thickness of Cover Material (m)	0	0	0
Density of Cover Material (g/m ³)	N/A	N/A	N/A
Cover Erosion Rate (m/yr)	N/A	N/A	N/A
Contaminated Zone Area (m ²)	-	242,000	-
Thickness of the Contaminated Zone (m)	-	0.15	-
Density of Contaminated Zone (g/cm ³)	-	1.28	-
Contaminated Zone Erosion Rate (m/yr)	0.00017	0.00034	0.00052
Length Parallel to the Aquifer Flow (m)	-	450	-
Dilution Length	0.03	3	250
Soil Mass Loading (g/m ³)	0.0000209	0.0000591	0.0002
Time Since Material Placement (yr)	-	0	-
Shape Factor (dimensionless)	-	1.0	-

distribution as shown by Eq. 4.3 (EG&G EM, 1990).

$$C(z) = C_0 e^{-\alpha z} \quad (4.3)$$

where,

$C(z)$	=	activity concentration at depth z , pCi/g
C_0	=	the surface concentration, pCi/g
α	=	exponential concentration factor, cm^{-1}
z	=	depth in soil, cm

"The exponential equation is in the form of $e^{-\alpha z}$, with alpha (α) being the inverse relaxation depth. At one relaxation depth, that volume of soil will contain 63% of the total activity. At a relaxation depth of two, that volume will contain 86% of the total activity, and at a relaxation depth of three, that volume will contain 95% of the total activity" (EG&G EM, 1990). Physical data were taken from a soil sampling survey conducted by Krey and Hardy in 1970 (EPA, 1976). The data indicate that 95% of the plutonium is distributed in the top 15 cm of soil. Americium and plutonium are assumed to be distributed homogeneously in the same manner. However, the Aerial Radiological Survey indicates that americium is exponentially distributed with a relaxation depth between 7 and 10 cm, suggesting that a slight amount of leaching has occurred. Thus, the contaminated zone thickness could potentially be as large as 30 cm.

The cover depth is a critical parameter in the RESRAD calculations. It reduces the amount of resuspended dust from the contaminated zone and the amount of plant roots in contact with the contaminated zone and acts as a buffer against erosion. However, none of the contaminated areas has any cover. The thickness of cover material is 0 m; parameters related to cover, such as the cover density and cover erosion rate, are not applicable to the calculations.

As discussed in Sect. 4.2.1.1.2, the contaminated zone, the vadose zone, and the

saturated zone strata are assumed to be relatively homogenous. The typical bulk soil density for the contaminated zone is 1.28 g/cm^3 .

The contaminated zone erosion rate is the average volume of soil material that is removed from the contaminated area by running water or wind per unit of ground surface and per unit of time. The erosion rate for the off-site areas, estimated by the Universal Soil Loss Equation (USLE) and presented in the *RFI/RI Work Plan for Operable Unit No. 3*, ranges from 1 to 3 tons/acre/year (2.2 to 6.7 metric tons/hectare/year) with an assumed average rate of 2 tons/acre/year (4.4 metric tons/hectare/year). Additional hand calculations verify the above rates. Applying the bulk soil densities for each of the areas results in an erosion rate of 0.00015 m/yr to 0.00047 m/yr with a mean of 0.00031 m/yr for the on-site area.

"The length parallel to the aquifer flow is the distance, in meters (m), between two parallel lines perpendicular to the direction of aquifer flow, one at the up-gradient edge of the contaminated zone and the other at the downgradient edge" (Yu, 1992). This length was calculated from potentiometric surface data in Fig. 2.4 of the *Phase II RFI/RI Work Plan Alluvial*. The potentiometric surface map indicates that groundwater flows to the east.

The dilution length is a parameter in the mixing model used to estimate the dilution of contaminated dust that is resuspended on-site by uncontaminated dust blown in from off-site. The dilution length is dependent upon the mixing height, resuspension rate, wind speed, and thickness of the resuspendable dust layer. The dilution length varies from 0.03 to 250 m with a mean value of 3 m. No site-specific data were available for the dilution length.

The mass loading factor is the concentration of soil particles in air. It is

dependent on both the conditions on the site and land use (as determined by the scenario). The *Rocky Flats Plant Site Environmental Report* for 1989 presents air monitoring data for Total Suspended Particulates (TSP) and Particulate Matter-10 μm or less (PM-10). The PM-10 data represent respirable-sized particulates. The arithmetic mean of the mass loading for 1989 was $20.9 \mu\text{g}/\text{m}^3$ with a 24-hour maximum value of $42.5 \mu\text{g}/\text{m}^3$. These values reflect a "no activity" mass loading for the OU 2 area. Higher mass loading factors will result from activity on the site. The *Draft Data Collection Handbook for Establishing Residual Radioactive Material Guidelines with RESRAD* suggests that the estimated mass loading factor for agriculture-generated dust is about 3.0×10^{-4} . The manual also suggests that the estimated mass loading factor, taking into account short periods of high mass loading and sustained periods of normal farmyard activities for which the dust level may be somewhat higher than ambient, is $2.0 \times 10^{-4} \text{ g}/\text{m}^3$. The nominal mass loading factor assumes a 4-month period, 10 hours/day (1200 hours/year), where the mass loading is 3.0×10^{-4} , and the rest of the time, 14 hours/day for 4 months (1680 hours/year), and 24 hours/day for 8 months (5880 hours/year) where the mass loading is 2.09×10^{-5} . These conditions generate a value of $5.91 \times 10^{-5} \text{ g}/\text{m}^3$. The highest value for the mass loading factor is assumed to be the suggested guideline of $2.0 \times 10^{-4} \text{ g}/\text{m}^3$ and the lowest value for the mass loading factor is assumed to be mean recorded "no activity" mass loading for 1989, 2.09×10^{-5} .

The parameter of time since material placement is the length of time that has passed (years) since the placement of initial radioactive material into the soil or since a soil contamination survey was conducted. The RESRAD manual suggests that an appropriate representative value should be input for all waste materials if the radioactive material was disposed of over a period of time. In addition, a value greater than zero

must be specified if groundwater concentrations are to be input.

The release of plutonium and americium from drums at the 903 Drum Storage Area occurred from 1958 to 1967, but the parameter of time since material placement is based on the date of the soil surveys (1989 and 1990) from which the soil contaminant concentration data are taken.

4.3.2 Initial Soil Contamination

4.3.2.1 Contaminated Zone Modeling

The RESRAD manual outlines three models for determining contamination of the zone: the homogenous, the conservative nonhomogeneous, and the nonhomogeneous models. The homogenous model assumes the radionuclides are relatively uniformly distributed within the contaminated zone.

"The potential annual individual dose received through a particular pathway is an areal average of the nonuniform residual radioactivity over an area determined by the scenario activities; for example, the area of daily activities for external radiation or the size of the garden for plant food pathways. For the purpose of deriving soil guidelines, it is assumed that this area is 100 m² for all pathways. The effect of vertical nonuniformities is taken into account by averaging over the radionuclide concentrations in a 0.15-m-thick layer. Thus, the criterion for releasing a site for use without radiological restrictions is as follows: for any 100-m² area and 0.15-m-thick layer within the contaminated zone...." (Yu, 1992).

$$\sum \bar{M}(t) = \sum_i \frac{\bar{S}_i(0)}{G_i(t)} \leq 1, \quad t_r \leq t \leq t_h \quad (4.4)$$

where,

- $\bar{M}(t)$ = average mixture sum at time t (dimensionless),
- $\bar{S}_i(t)$ = initial concentration of the i th principal radionuclide averaged over a 100-m² area and 0.15-m-thick layer (pCi/g), and
- $G_i(t)$ = single-radionuclide soil concentration guideline for the i th principal radionuclide in a uniformly contaminated zone at time t (pCi/g).

Equation 3.2 is the homogenous release criteria. It directly applicable to homogenous contamination, which is defined as contamination in a volume within which radionuclide concentrations in individual soil samples do not exceed the average concentrations by a factor larger than 3. However, the distribution of Pu and Am in the contaminated areas is very nonhomogeneous (i.e., the maximum concentrations exceed the average by a factor significantly larger than 3). Thus, the conservative nonhomogeneous approach is taken. The conservative nonhomogeneous model uses the homogenous release criteria but replaces the average concentration, S_i , with one-third of the maximum concentration, $S_i/3$. This approach is suggested in Chapter 3 of the RESRAD manual.

4.3.2.2 Soil Contaminant Concentration Data

4.3.2.2.1 Operable Unit 2

The maximum concentration of americium-241 in the on-site area as indicated in the 1990 In Situ Survey is 91.0 pCi/g. The maximum concentrations of the various isotopes of plutonium are given by multiplying the maximum concentration of americium-241 by the ratio factor and the relative weight given in Table 4.9. The sum of the relative

Table 4.9. Isotopic Composition of Plutonium at Rocky Flats

Isotope	Relative Weight (%)
Pu-238	0.01
Pu-239	93.79
Pu-240	5.8
Pu-241	0.36
Pu-242	0.03

Source: "Final Past Remedy Report, Operable Unit No. 3 - IHSS 199," U.S. Department of Energy, April 1991

weights of Pu-238, Pu-241, and Pu-242 is only 0.4 percent. For this reason these three radionuclides have been neglected for the assessment. The maximum concentrations of Pu-239, Pu-240, and Am-241 are 532, 33, and 91 pCi/g respectively. The initial concentrations are obtained by dividing these maximum concentrations by 3 as per the conservative inhomogeneous approach suggested in the RESRAD manual. They are listed in Table 4.10.

4.3.2.2.1.1 Northern Off-Site Area

The maximum concentration of Pu-239 and Pu-240 in the northern off-site area as indicated in the 1990 EPA survey is 6.47 pCi/g. The maximum concentrations of the various isotopes of plutonium were calculated by multiplying these concentrations by the relative weights. The maximum concentration of Am-241 was calculated by dividing the maximum concentration of Pu-239 and Pu-240 by the ratio factor. The maximum concentrations of Pu-239, Pu-240, and Am-241 are 6.07, 0.38, and 1.04 pCi/g respectively. The initial concentrations were obtained by dividing these maximum concentrations by 3. They are listed in Table 4.10.

4.3.2.2.1.2 Southern Off-Site Area

The maximum concentration of Pu-239 and Pu-240 in the southern off-site area as indicated in the 1990 EPA annual remedy acreage survey is 1.74 pCi/g. The maximum concentrations of the various isotopes of plutonium were calculated by multiplying these concentrations against the relative weights. The maximum concentration of Am-241 was calculated by dividing the maximum concentration of Pu-239 and Pu-240 by the ratio factor.

The maximum concentrations of Pu-239, Pu-240, and Am-241 are 1.63, 0.1, and 0.28 pCi/g respectively. The initial concentrations were obtained by dividing these maximum

concentrations by 3. They are listed in Table 4.10.

Table 4.10. Initial Soil Concentrations

Radionuclide	Initial Soil Concentration (pCi/g)		
	On-Site Area	Northern Off-Site Area	Southern Off-Site Area
Am-241	30	0.35	0.28
Pu-238	Neglected ¹	Neglected ¹	Neglected ¹
Pu-239	177	2.03	1.64
Pu-240	11	0.13	0.10
Pu-241	Neglected ¹	Neglected ¹	Neglected ¹
Pu-242	Neglected ¹	Neglected ¹	Neglected ¹

¹Pu-238, -241, and -242 compose less than 1% of the total plutonium

5. RESULTS

The dose to the receptor is highly dependent on the distribution coefficients (K_d), especially for americium. This parameter is the most sensitive in the assessment. It determines whether Am-241 reaches the groundwater aquifer in sufficient quantities to produce a significant dose from water-dependent pathways before it is removed from the source by wind and water erosion. The three cases considered for K_d are low, nominal (average), and high values. For plutonium, the value suggested for the type of soil at RFP in the *Draft Data Collection Handbook for Establishing Residual Radioactive Material Guidelines with RESRAD* is 1200 cm³/g. The lowest value, for sand, is 550 cm³/g, and the highest value is considered to be 2000 cm³/g, the suggested default value and an average of the distribution coefficients of the different soil types. Americium usually has a distribution coefficient slightly lower than that of plutonium. The *Draft Data Collection Handbook for Establishing Residual Radioactive Material Guidelines with RESRAD* suggests a default value of 20 cm³/g. However, for this assessment, this value is considered to be the lower value. The nominal value is considered to be 200 cm³/g, and the high value is considered to be the nominal for plutonium, at 2000 cm³/g.

5.1 On-Site Contaminated Area

5.1.1 Nominal Distribution Coefficients

The total dose to the receptor for the on-site contaminated area is shown in Fig. 5.1. The maximum total dose at time zero (1990 A.D.) is approximately 60 mrem and it slowly declines over a 450-year period. This dose is contributed by Am-241, Pu-239, and Pu-240. Figures 5.2, 5.3, and 5.4 show the respective contributions. The maximum dose from Am-241, summed over all pathways at time zero (1990) is approximately 9 mrem, or 15% of the total dose. The maximum dose from Pu-239, summed over all pathways at

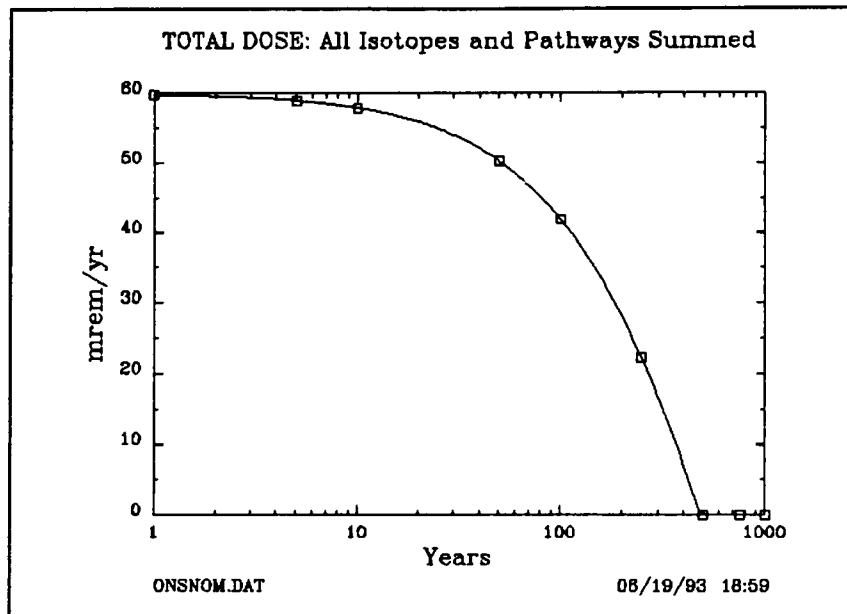


Figure 5.1. Total Dose for the On-Site Area, All Isotopes and Pathways Summed

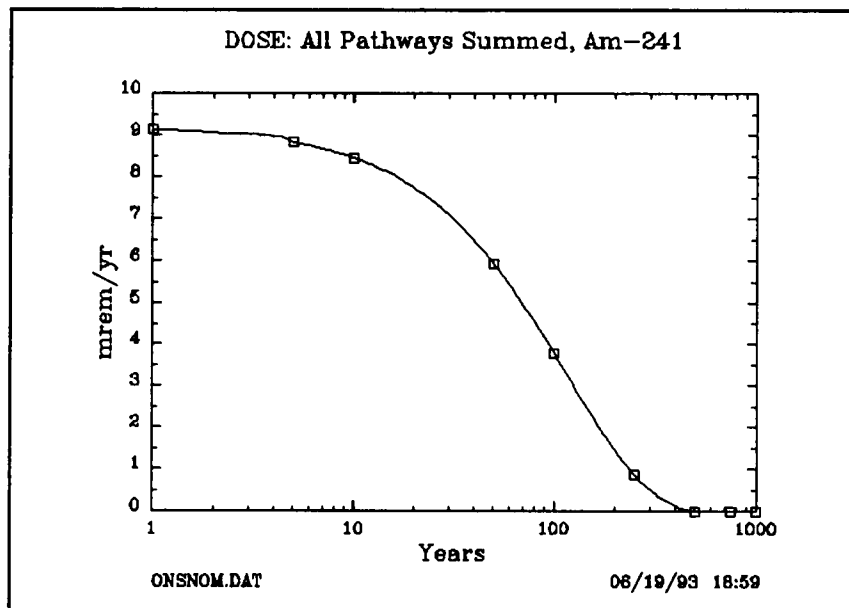


Figure 5.2. Dose From Am-241, Summed Over All Pathways

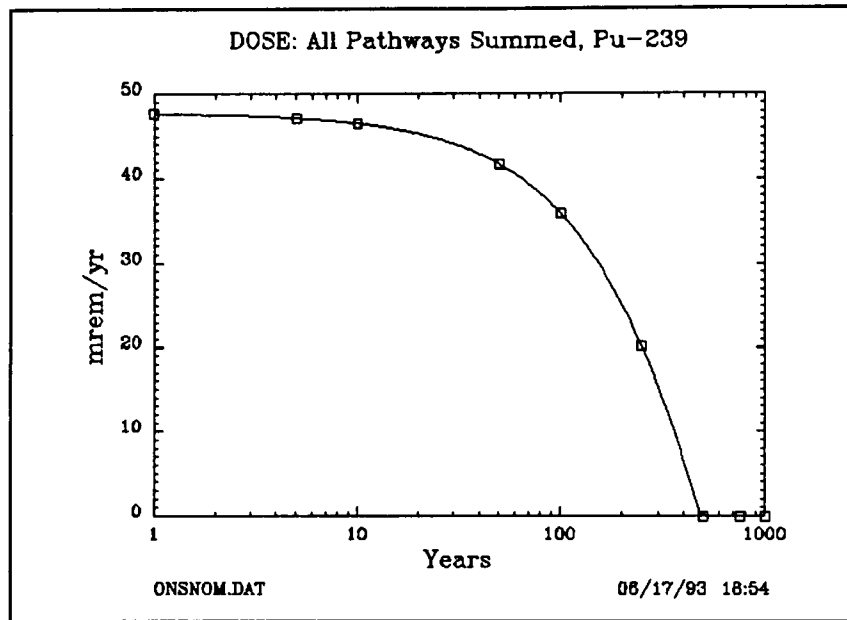


Figure 5.3. Dose From Pu-239, Summed Over All Pathways

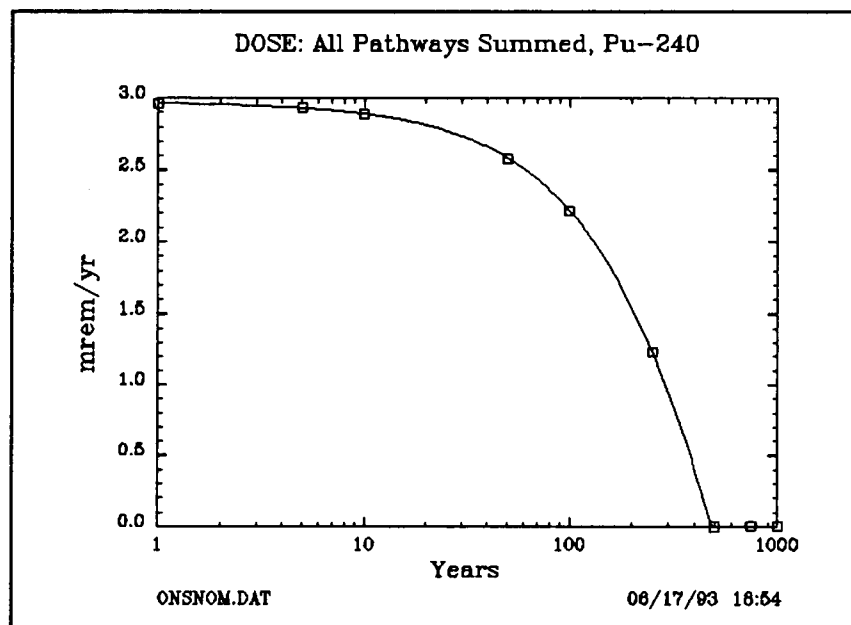


Figure 5.4. Dose From Pu-240, Summed Over All Pathways

time zero (1990) is approximately 48 mrem, or 80% of the total dose. Lastly, the maximum dose at from Pu-240, summed over all pathways at time zero (1990) is approximately 3 mrem, or 5% of the total dose.

The nine pathways may be divided into water-independent and water-dependent pathways. Some of the pathways (plant, meat, and milk) are both. For these pathways, the dose is divided into water-independent and water-dependent fractions. Figures 5.5, 5.6, and 5.7 show the dose summed over water-independent and water-dependent pathways, respectively. The doses for each of the radionuclides summed over all pathways are the result of almost entirely water-independent pathways. The doses from water-dependent pathways are negligible.

Figures 5.8, 5.9, and 5.10 illustrate the dose received by individual water-independent pathways. Dust inhalation and soil ingestion produced the highest doses. Both pathways contribute approximately 26 mrem/yr (43% of the total dose) each. The plant and meat ingestion pathways produce approximately 5.2 mrem/yr (8.6% of the total dose) and 2.1 mrem/yr (3.6% of the total dose). Direct ground radiation produces 0.95 mrem/yr (1.8% of the total dose). Milk ingestion produced the smallest dose, 0.00015 mrem/yr (a negligible fraction of the total dose).

5.1.2 High Distribution Coefficients

The high distribution coefficient value for both Pu and Am is $2000 \text{ cm}^3/\text{g}$. These distribution coefficients produce the same dose to the receptor as for the nominal case. Thus, an increase in the distribution coefficients from the nominal values results in no discernable change in the dose to the receptor in the on-site area.

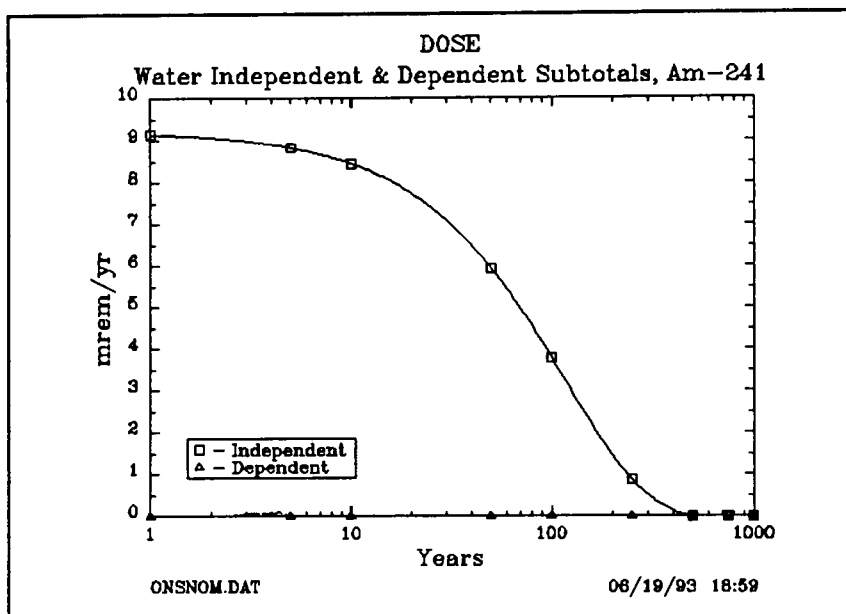


Figure 5.5. Dose From Am-241, Summed Over Water-Independent and Water -Dependent Pathways

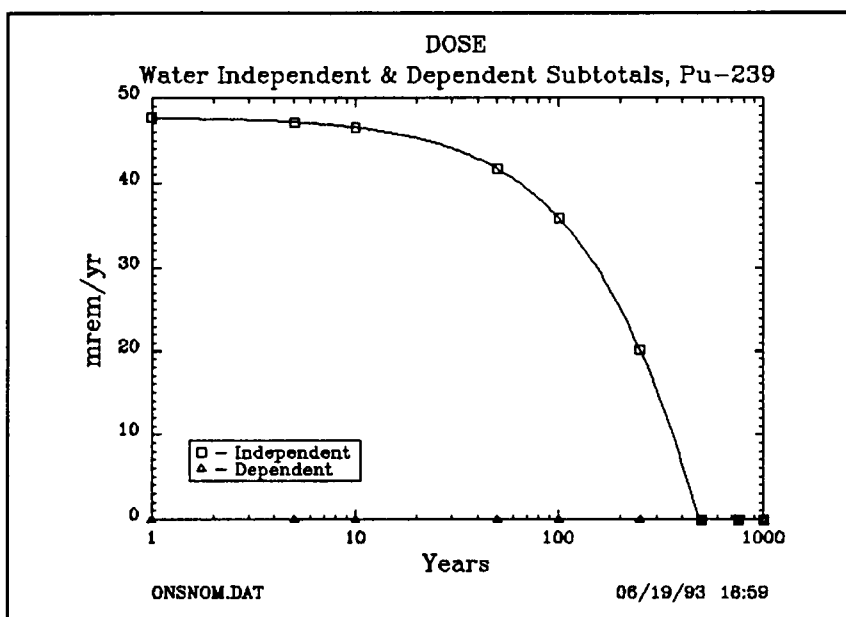


Figure 5.6. Dose From Pu-239, Summed Over Water-Independent and Water-Dependent Pathways

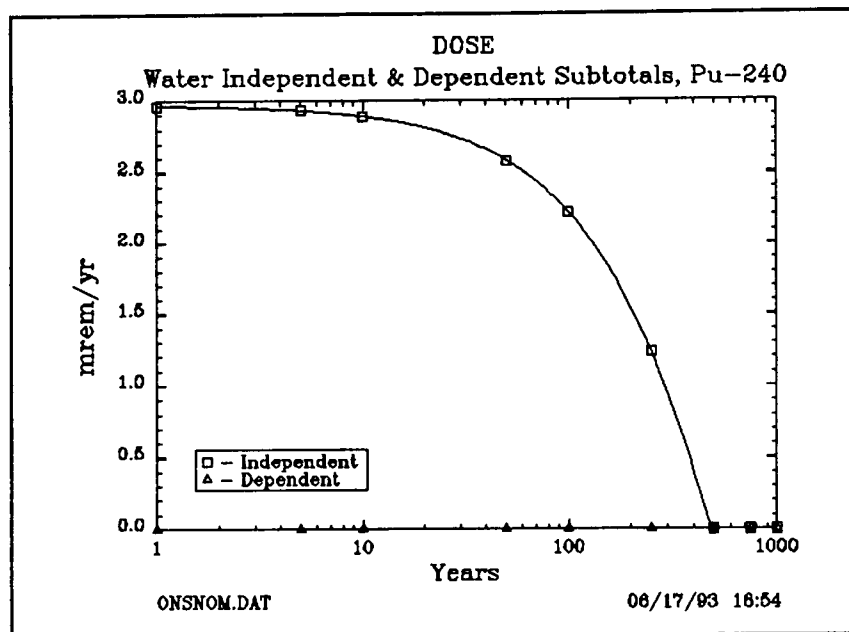


Figure 5.7. Dose From Pu-240, Summed Over Water-Independent and Water-Dependent Pathways

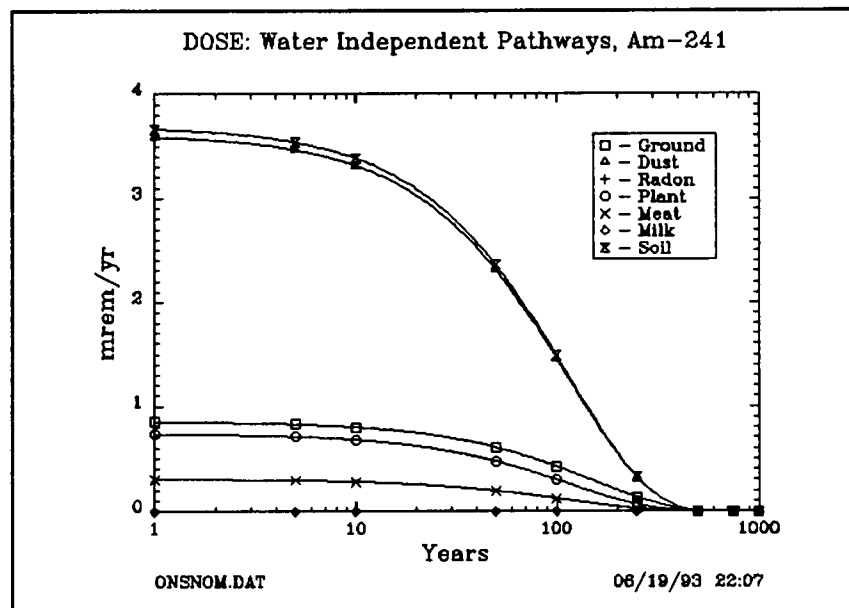


Figure 5.8. Dose From Am-241, Water-Independent Pathways

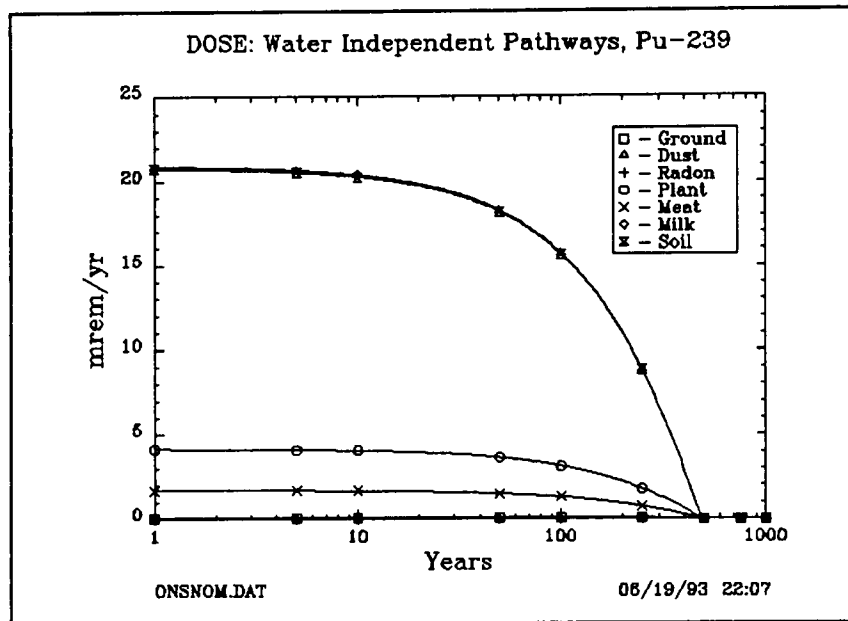


Figure 5-9. Dose From Pu-239, Water-Independent Pathways

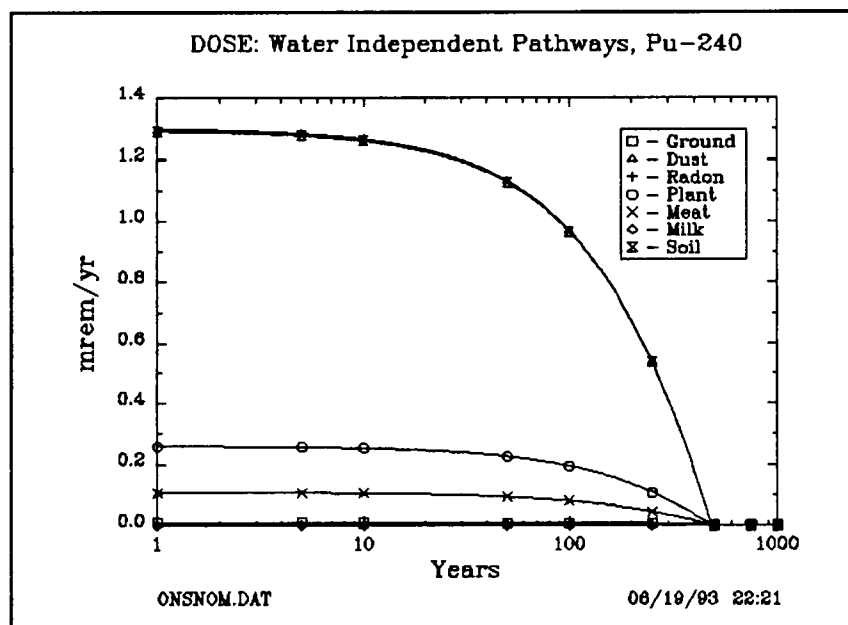


Figure 5-10. Dose From Pu-240, Water-Independent Pathways

5.1.3 Low Distribution Coefficients

The low distribution coefficient values for Pu and Am are $550 \text{ cm}^3/\text{g}$ and $20 \text{ cm}^3/\text{g}$, respectively. These distribution coefficients produce a significantly larger dose to the receptor than for the nominal case. The total dose to the receptor is shown in Fig. 5.11. Unlike the total dose shown in Fig. 5.1 for higher distribution coefficients, the dose consists of two peaks. The first peak is identical to that shown in Fig. 5.1. The second is the result of Am-241, which is transported to the groundwater and produces a dose from water-independent pathways.

Figures 5.12, 5.13, and 5.14 illustrate the contributions by Am-241, Pu-239, and Pu-240 to the total dose. The contributions to the first peak are identical to that for the nominal and high distribution coefficient values. Am-241 contributes 420 mrem/yr (100% of the total dose) to the second peak.

Figures 5.15, 5.16, and 5.17 illustrate the contributions by the three radionuclides, summed over water-independent and water-dependent pathways. The dose from the three radionuclides for the first peak result completely from water-independent pathways. However, the dose for the second peak results completely from water-dependent pathways.

Figure 5.18 illustrates the dose from individual water-dependent pathways for Am-241. Drinking water ingestion produces the highest dose, approximately 210 mrem/yr (50% of the total dose) at about 350 years (2340). Plant and meat ingestion contribute most of the remaining dose. Meat ingestion produces approximately 108 mrem/yr (26% of the total dose) and plant ingestion produces approximately 99 mrem/yr (23% of the total dose). The remaining dose is produced from fish and milk ingestion pathways. Fish ingestion produces approximately 3.5 mrem/yr (about 1% of the total dose) and milk

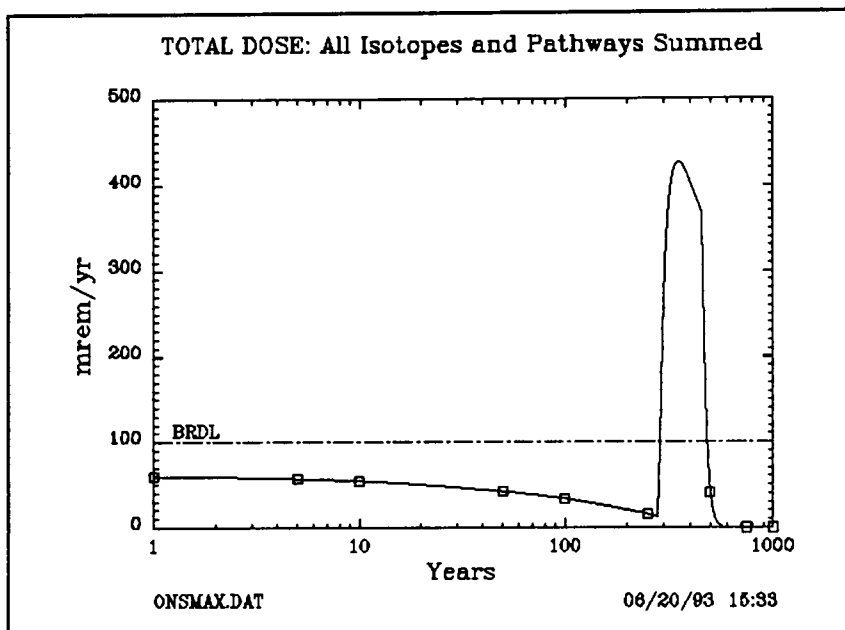


Figure 5.11. Total Dose for the On-Site Area, All Isotopes and Pathways Summed, Low K_d Value

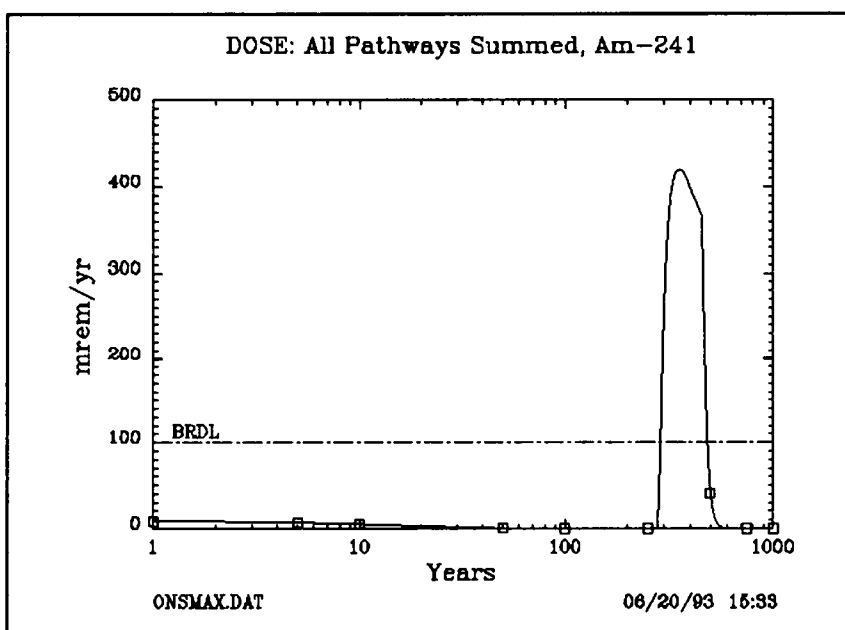


Figure 5.12. Dose From Am-241, Summed Over All Pathways, Low K_d Value

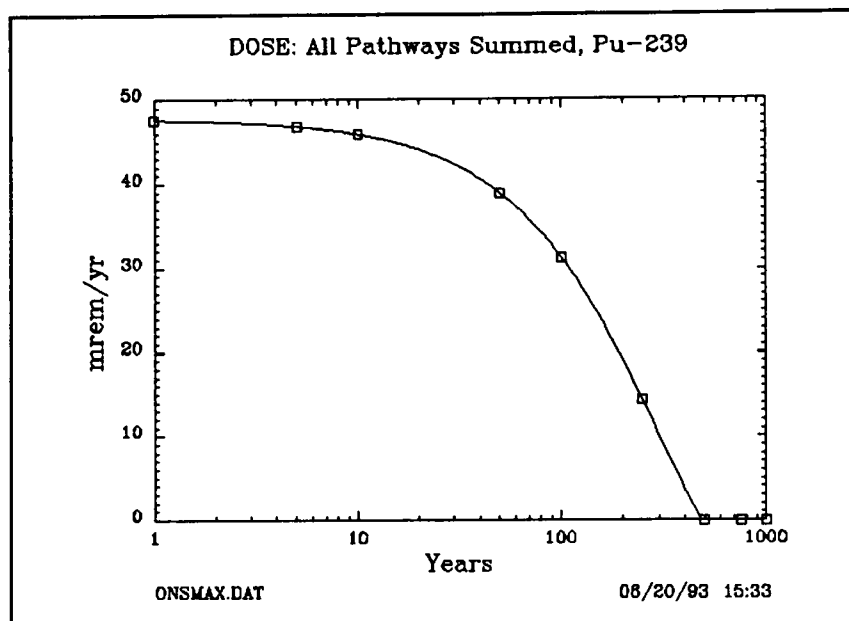


Figure 5.13. Dose From Pu-239, Summed Over All Pathways, Low K_d Value

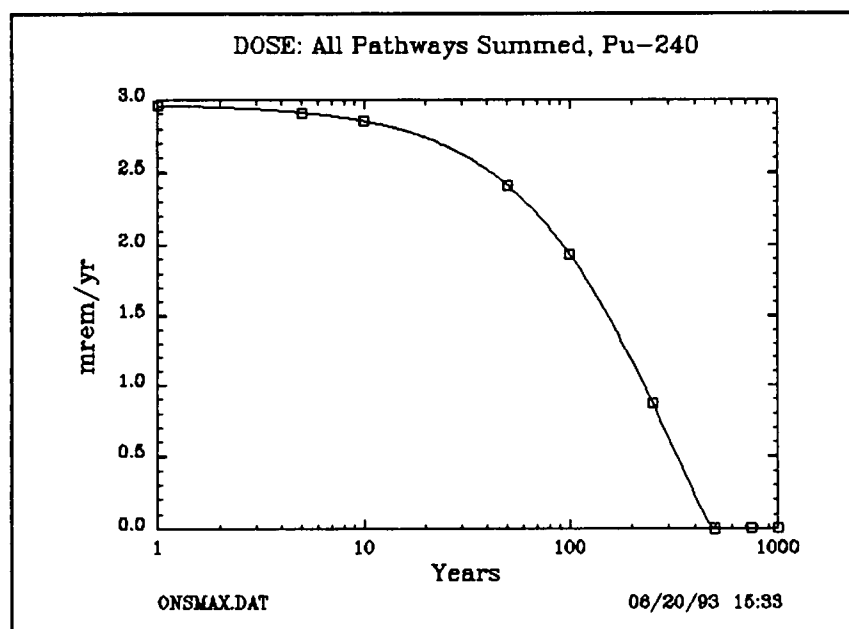


Figure 5.14. Dose From Pu-240, Summed Over All Pathways, Low K_d Value

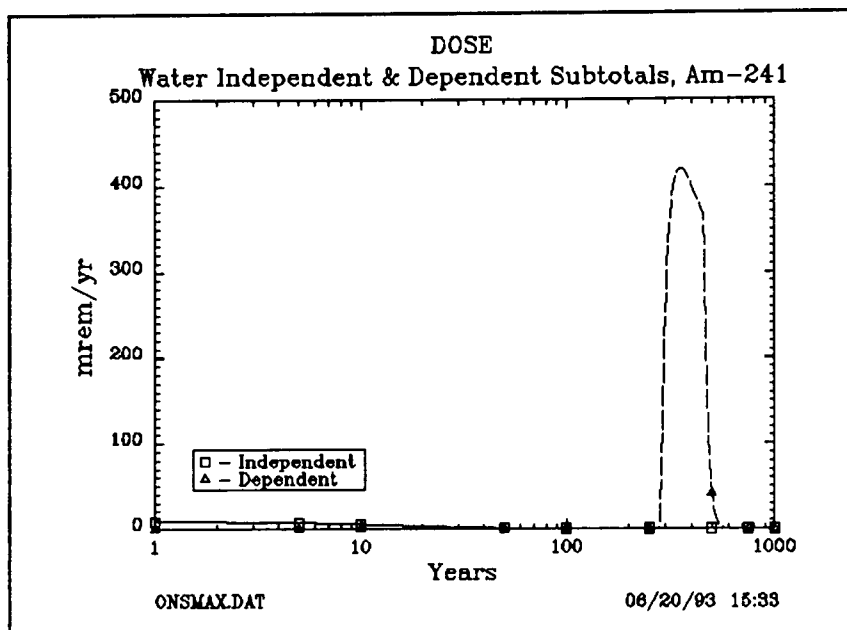


Figure 5.15. Dose From Am-241, Summed Over Water-Independent and Water-Dependent Pathways, Low K_d Value

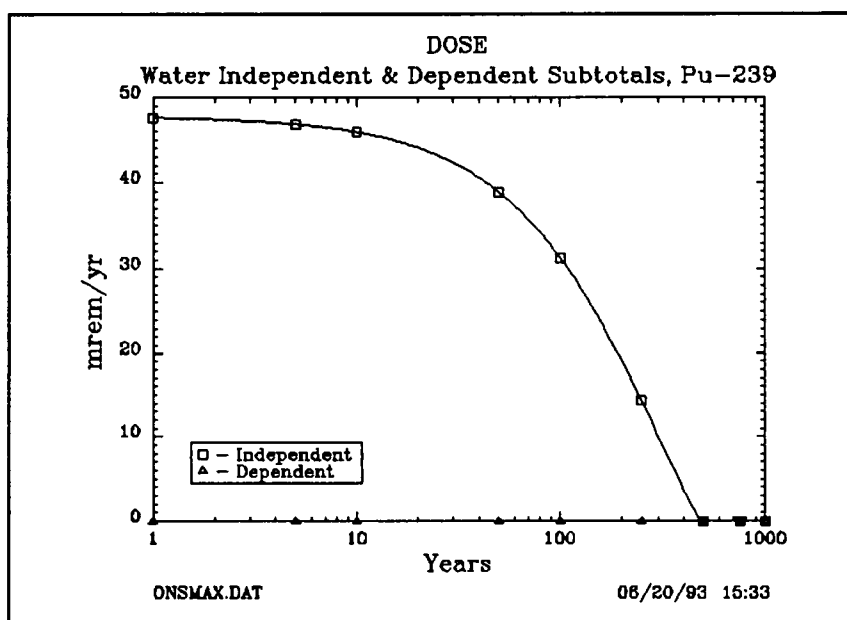


Figure 5.16. Dose From Pu-239, Summed Over Water-Independent and Water-Dependent Pathways, Low K_d Value

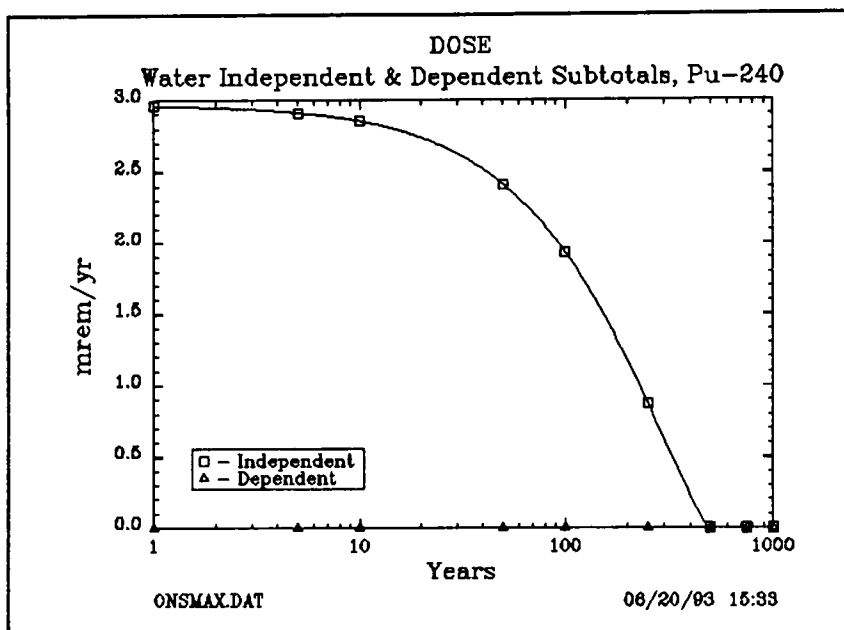


Figure 5.17. Dose From Pu-240, Summed Over Water-Independent and Water-Dependent Pathways, Low K_d Value

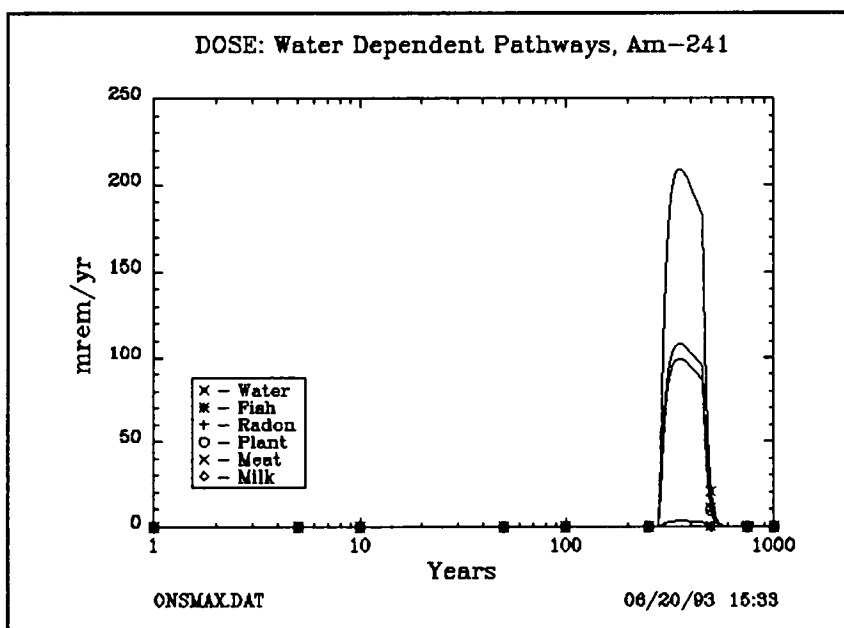


Figure 5.18. Dose From Am-241, Water-Dependent Pathways, Low K_d Value

ingestion produces approximately 0.064 mrem/yr (about 0.02% of the total dose).

5.2 NORTHERN OFF-SITE CONTAMINATED AREA

5.2.1 Nominal Distribution Coefficients

The total dose to the receptor for the northern off-site contaminated area shown in Fig. 5.19 is similar to that for the on-site contaminated area. The maximum total dose at time zero is approximately 0.68 mrem/yr and it slowly declines over a 450-year period. The individual contributions by Am-241, Pu-239, and Pu-240 are shown in Figs 5.20, 5.21, and 5.22, respectively. The maximum dose from Am-241, summed over all pathways at time zero, is approximately 0.11 mrem/yr (16% of the total dose). The maximum dose from Pu-239, summed over all pathways at time zero, is approximately 0.55 mrem/yr (79% of the total dose). Finally, the maximum dose from Pu-240, summed over all pathways at time zero, is approximately 0.035 mrem/yr (5% of the total dose).

Figures 5.23, 5.24, and 5.25 show the dose for each radionuclide summed over water-independent and water-dependent pathways. As in the case for the on-site contaminated area, the doses for each of the radionuclides summed over all pathways are the result of almost entirely water-independent pathways.

Figures 5.26, 5.27, and 5.28 illustrate the dose received by individual water-independent pathways for each of the three radionuclides. At the on-site area, dust inhalation and soil ingestion produce the highest dose. Soil ingestion contributes approximately 0.29 mrem/yr (43% of the total dose), and dust inhalation contributes approximately 0.30 mrem/yr (43% of the total dose). Plant ingestion contributes approximately 0.059 mrem/yr (8.7% of the total dose) and meat ingestion contributes approximately 0.024 mrem/yr (3.6% of the total dose). Direct ground radiation produces only 0.011 mrem/yr (1.6% of the total dose). Milk ingestion contributes an extremely

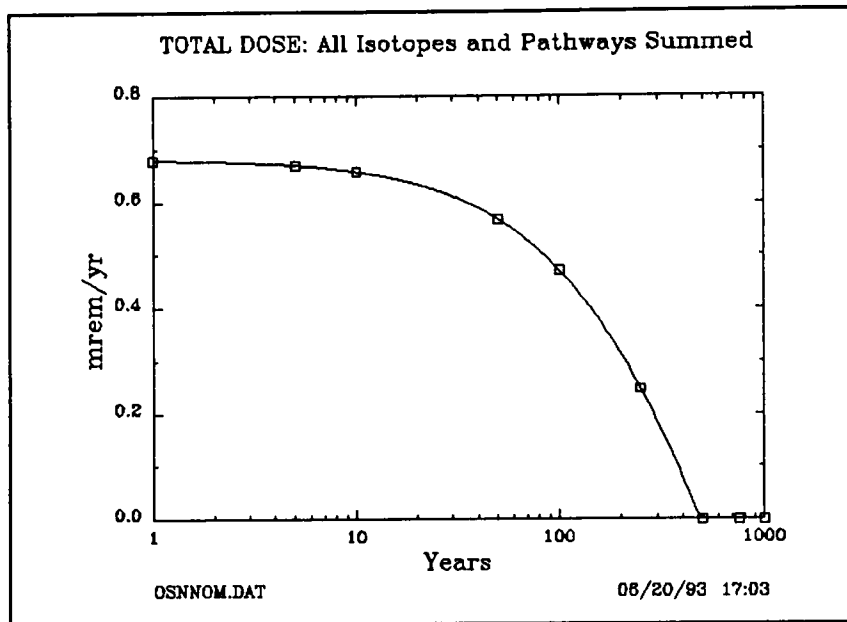


Figure 5.19. Total Dose From the Northern Off-Site Area, All Isotopes and Pathways Summed

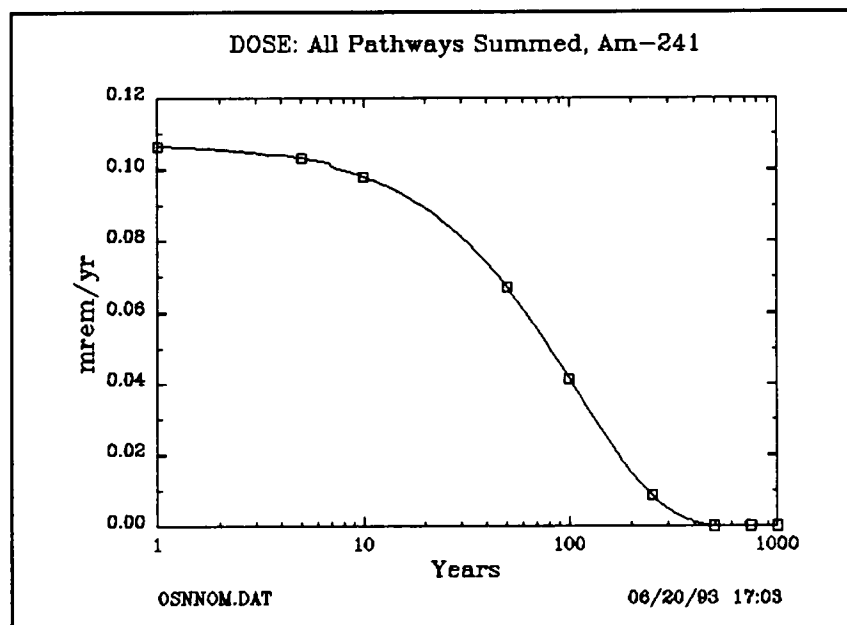


Figure 5.20. Dose From Am-241, Summed Over All Pathways

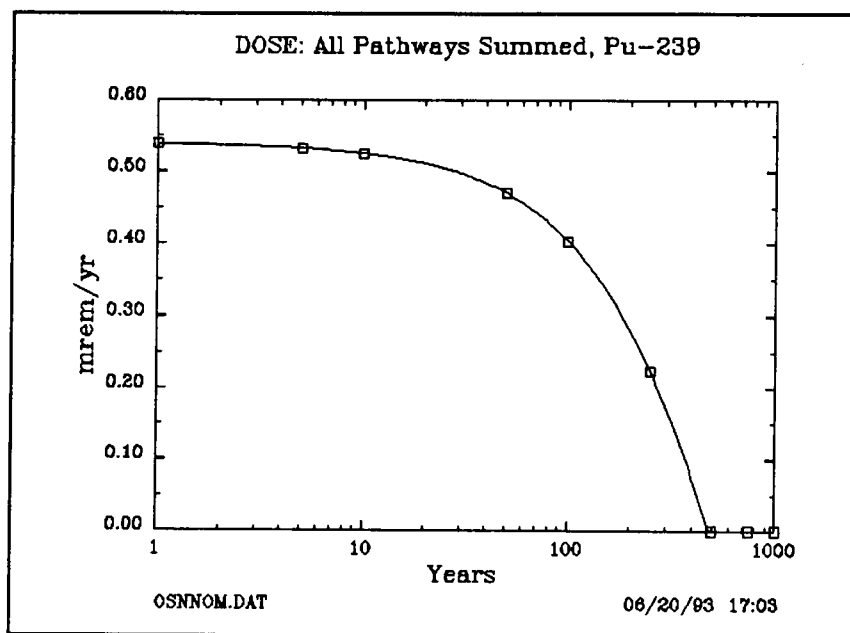


Figure 5.21. Dose From Pu-239, Summed Over All Pathways

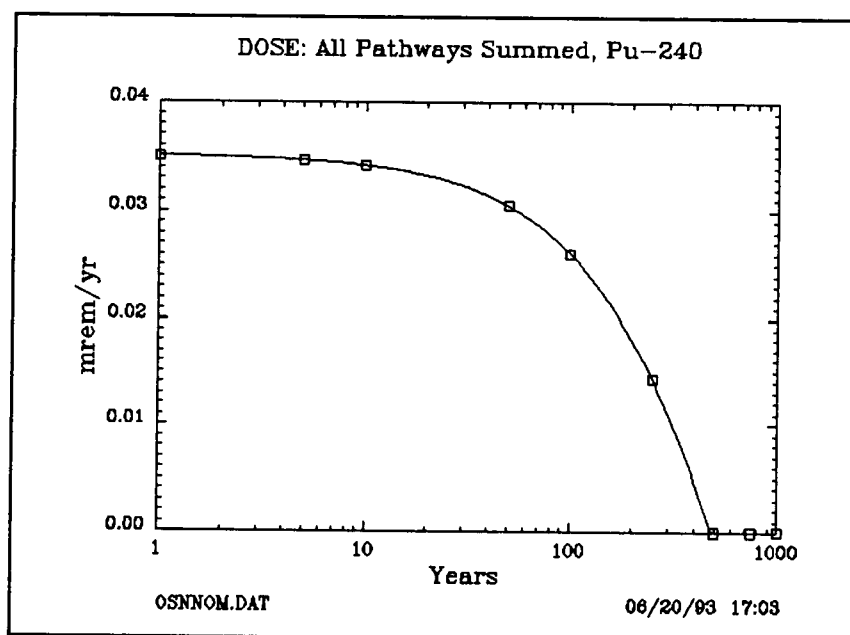


Figure 5.22. Dose From Pu-240, Summed Over All Pathways

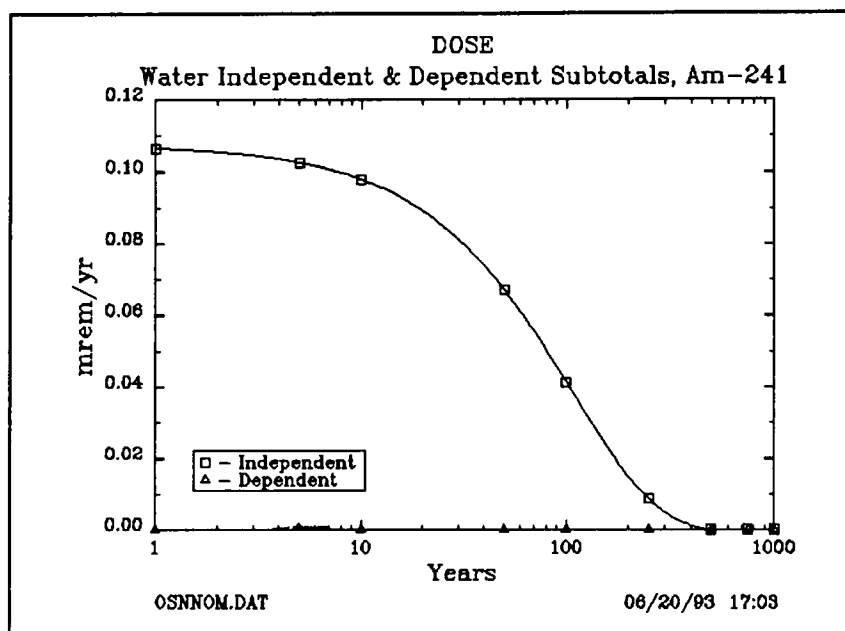


Figure 5.23. Dose From Am-241, Summed Over Water-Independent and Water-Dependent Pathways

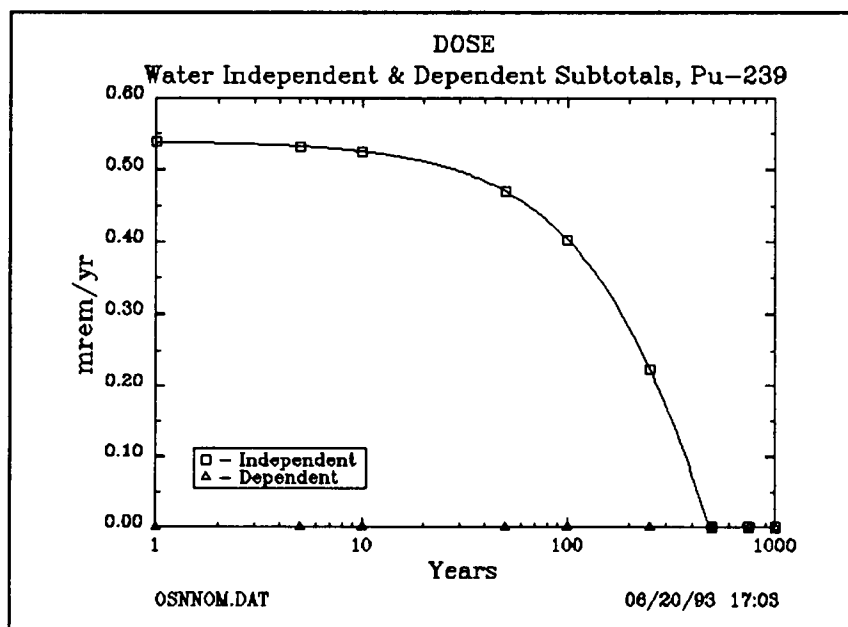


Figure 5.24. Dose From Pu-239, Summed Over Water-Independent and Water-Dependent Pathways

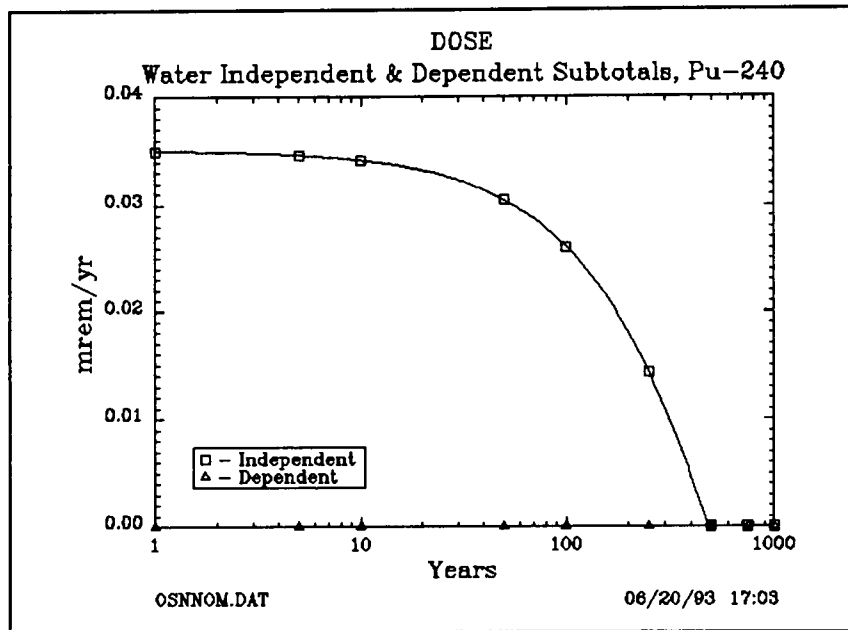


Figure 5.25. Dose From Pu-240, Summed Over Water-Independent and Water-Dependent Pathways

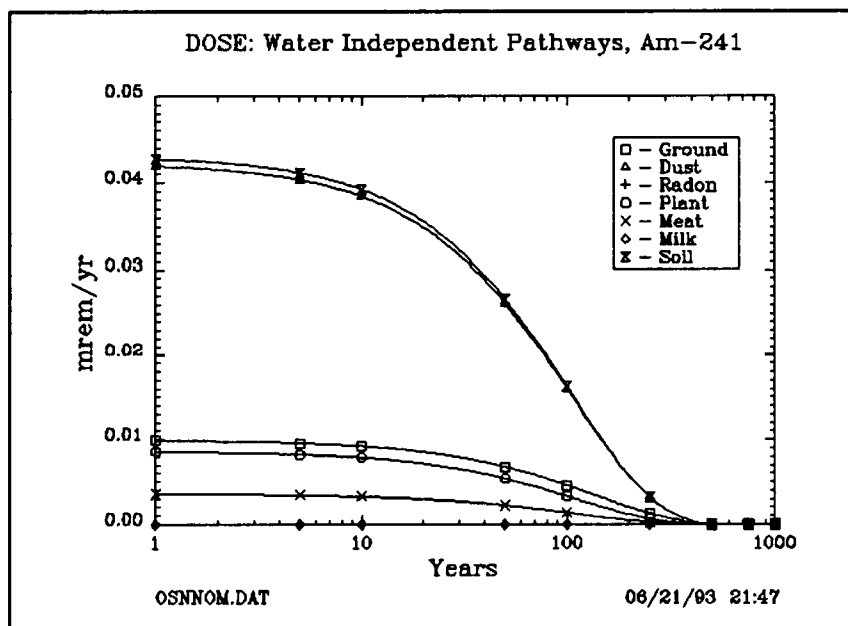


Figure 5.26. Dose From Am-241, Water-Independent Pathways

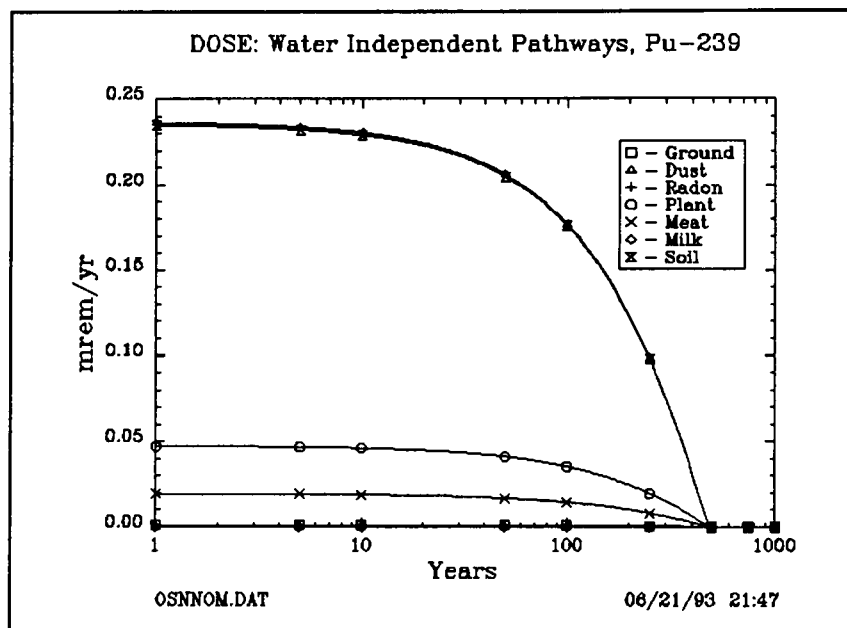


Figure 5.27. Dose From Pu-239, Water-Independent Pathways

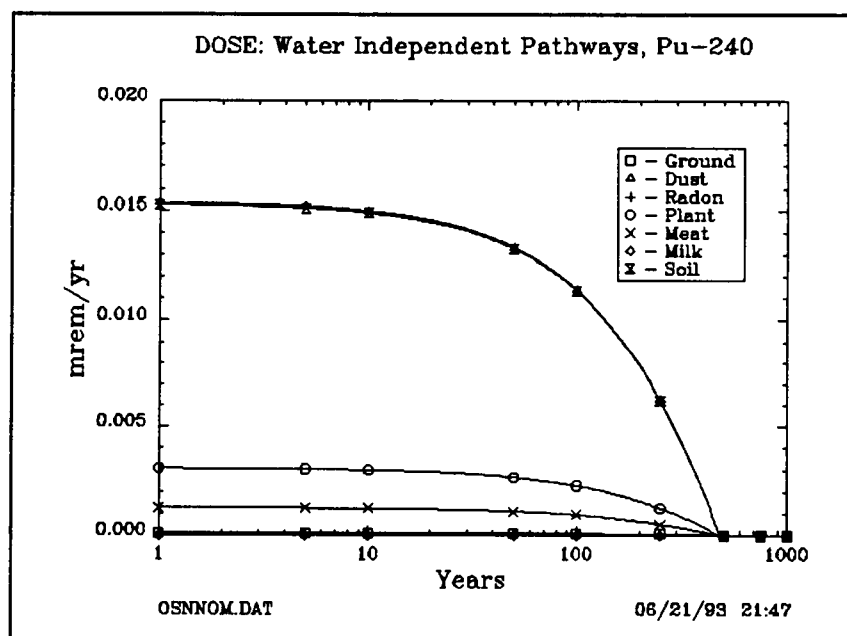


Figure 5.28. Dose From Pu-240, Water-Independent Pathways

small dose of 1.8×10^{-7} mrem/yr (essentially 0% of the total dose).

5.2.2 High Distribution Coefficients

The high distribution coefficient value for both Pu and Am is $2000 \text{ cm}^3/\text{g}$. As for the on-site contaminated area, these distribution coefficients produce the same dose to the receptor as for the nominal case. Thus, an increase in the distribution coefficients from the nominal values results in no discernable change in the dose to the receptor in the on-site area.

5.2.3 Low Distribution Coefficient

The low distribution coefficient values for Pu and Am are $550 \text{ cm}^3/\text{g}$ and $20 \text{ cm}^3/\text{g}$, respectively. This distribution coefficient produces a significantly larger dose to the receptor than that for the nominal case. The total dose to the receptor is shown in Fig. 5.29. Unlike the total dose shown in Fig. 5.19 for higher distribution coefficients, the dose consists of two peaks. The first peak is identical to that shown in Fig. 5.19. The second is the result of Am-241, which is transported to the groundwater and produces a dose from water-independent pathways.

Figures 5.30, 5.31, and 5.32 illustrate the contributions by Am-241, Pu-239, and Pu-240 to the total dose. The contributions to the first peak are identical to those for the nominal and high distribution coefficient values. Am-241 contributes 2.8 mrem/yr (100% of the total dose) to the second peak.

Figures 5.33, 5.34, and 5.35 illustrate the contributions by the three radionuclides, summed over water-independent and water-dependent pathways. The dose from the three radionuclides for the first peak results completely from water-independent pathways. However, the dose for the second peak results completely from water-dependent pathways.

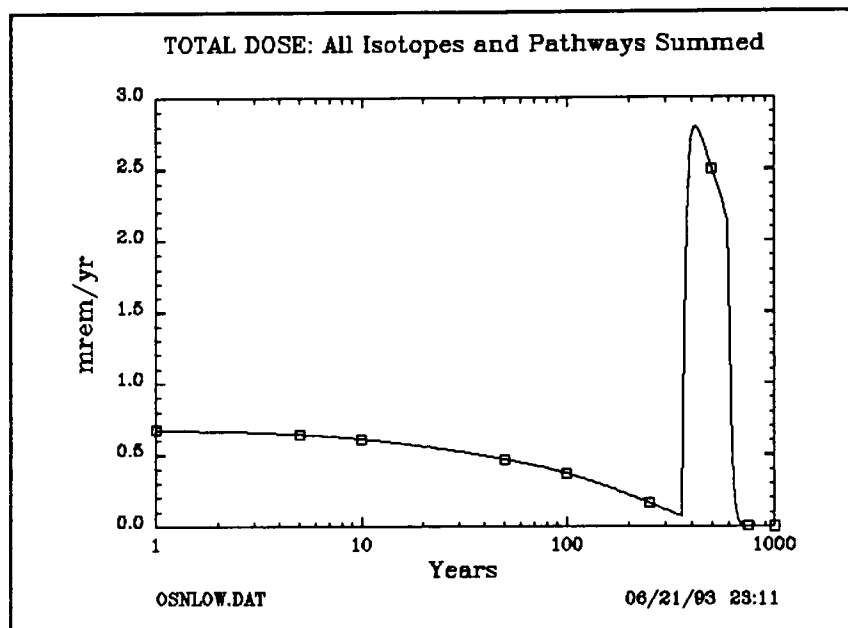


Figure 5.29. Total Dose for the Northern Off-Site Area, All Isotopes and Pathways Summed, Low K_d Value

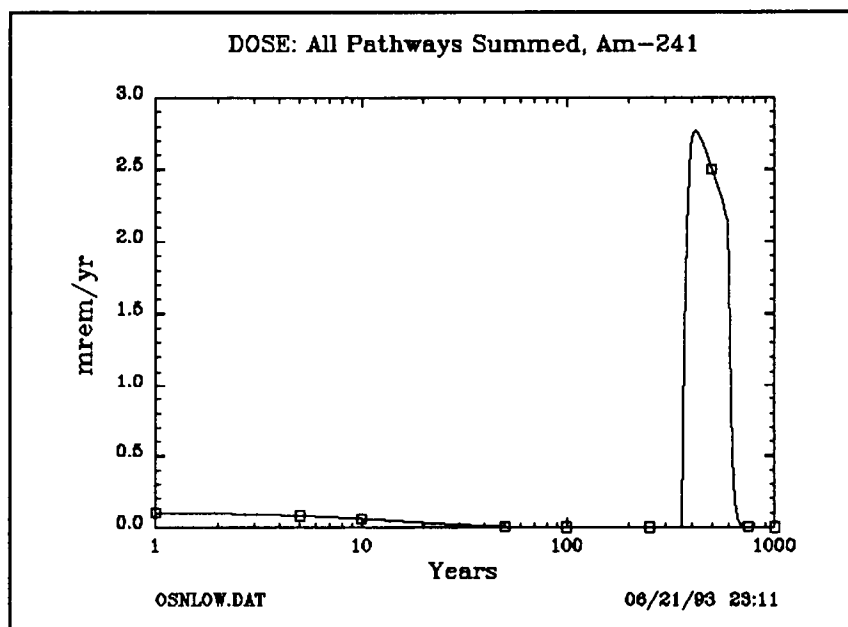


Figure 5.30. Dose From Am-241, Summed Over All Pathways, Low K_d Value

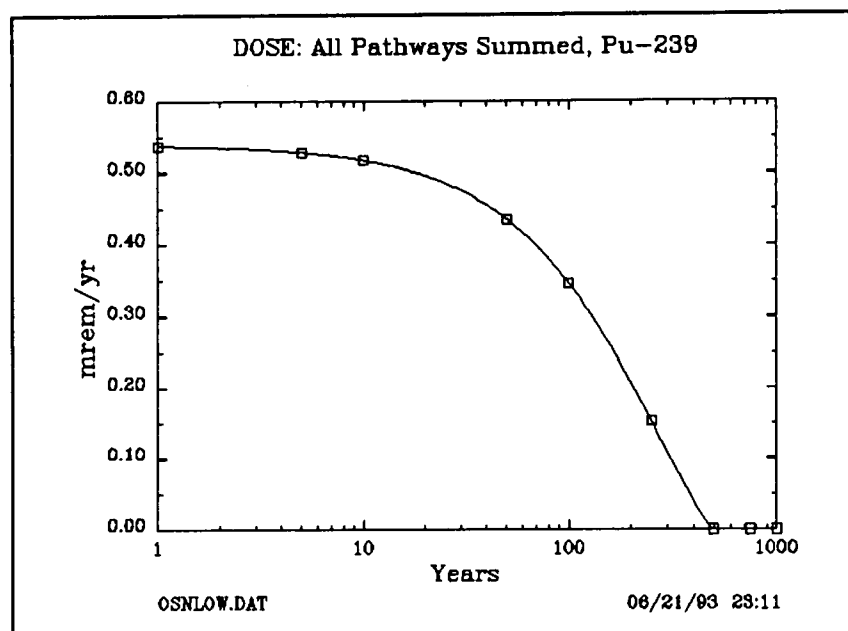


Figure 5.31. Dose From Pu-239, Summed Over All Pathways, Low K_d Value

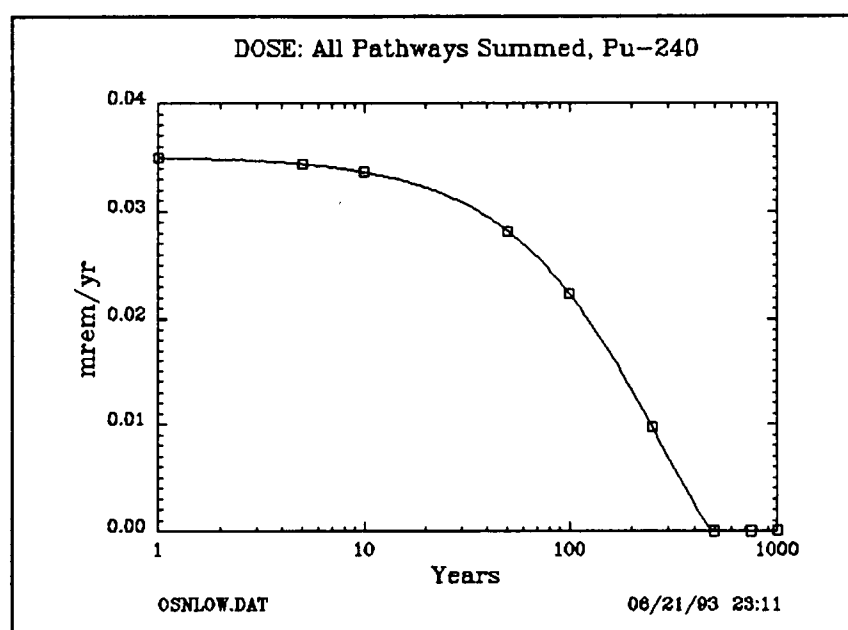


Figure 5.32. Dose From Pu-240, Summed Over All Pathways, Low K_d Value

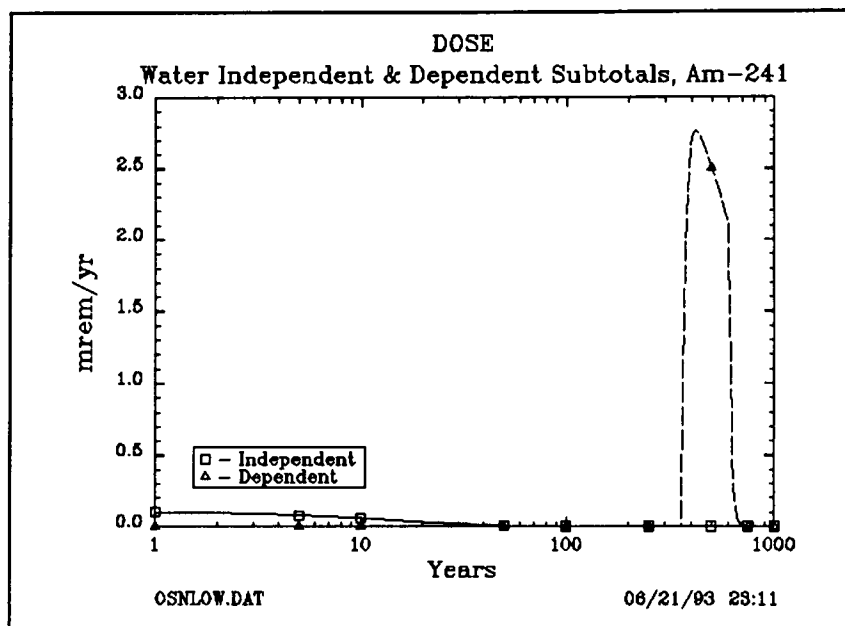


Figure 5.33. Dose From Am-241, Summed Over Water-Independent and Water-Dependent Pathways, Low K_d Value

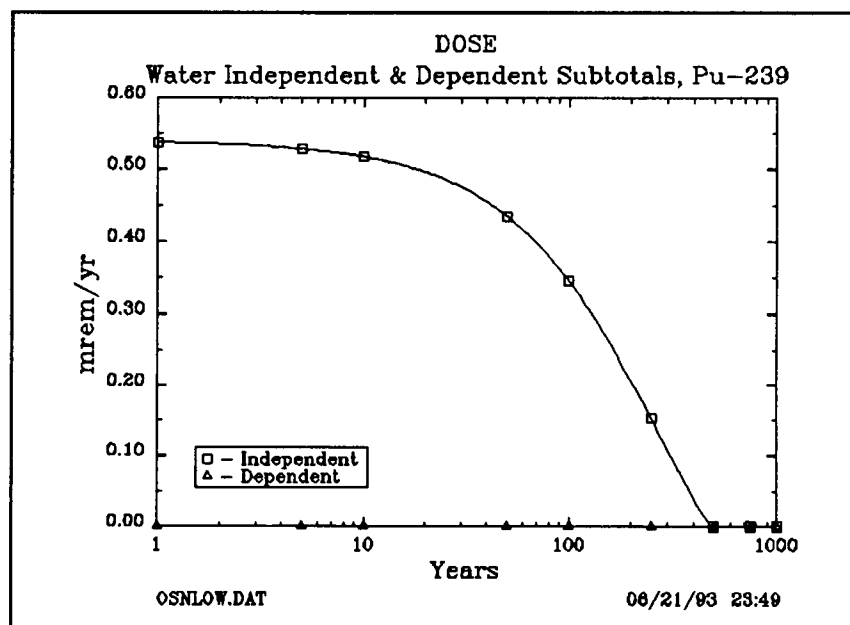


Figure 5.34. Pu-239 Dose, Summed Over Water-Independent and Water-Dependent Pathways, Low K_d Value

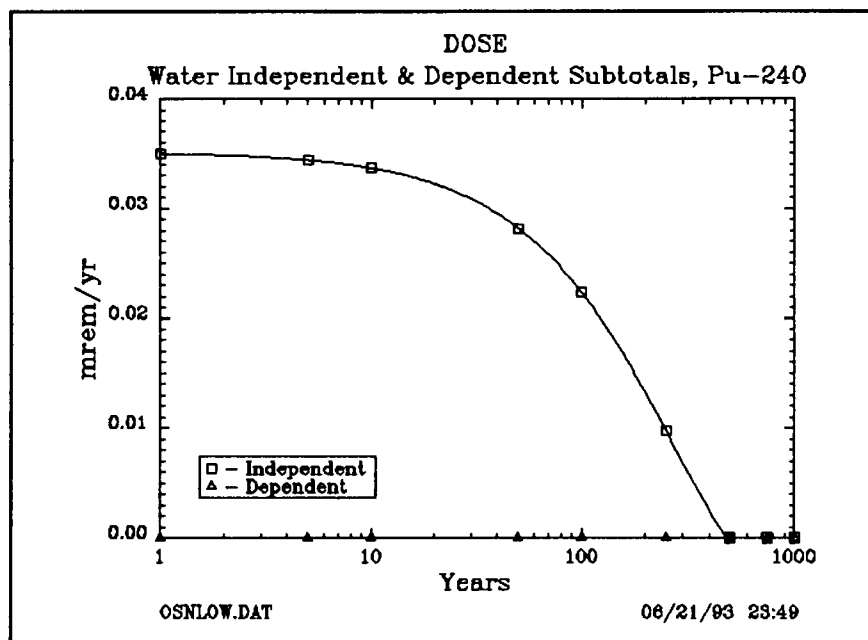


Figure 5.35. Dose From Pu-240, Summed Over Water-Independent and Water-Dependent Pathways, Low K_d Value

Figure 5.36 illustrates the dose from individual water-dependent pathways for Am-241. The maximum dose is 2.8 mrem/yr at 418 years (2408). Drinking-water ingestion produces the highest dose, approximately 1.4 mrem/yr (49% of the total dose). Plant and meat ingestion contributes most of the remaining dose. Plant ingestion produces approximately 0.65 mrem/yr (23% of the total dose), and meat ingestion produces approximately 0.71 mrem/yr (25% of the total dose). The remaining dose comes from fish and milk. Fish ingestion produces approximately 1.5 mrem/yr (1.5% of the total dose) and milk ingestion produces 0.00042 mrem/yr (about 0.02% of the total dose). In addition, dust inhalation produces 0.014 mrem/yr (0.5% of the total dose).

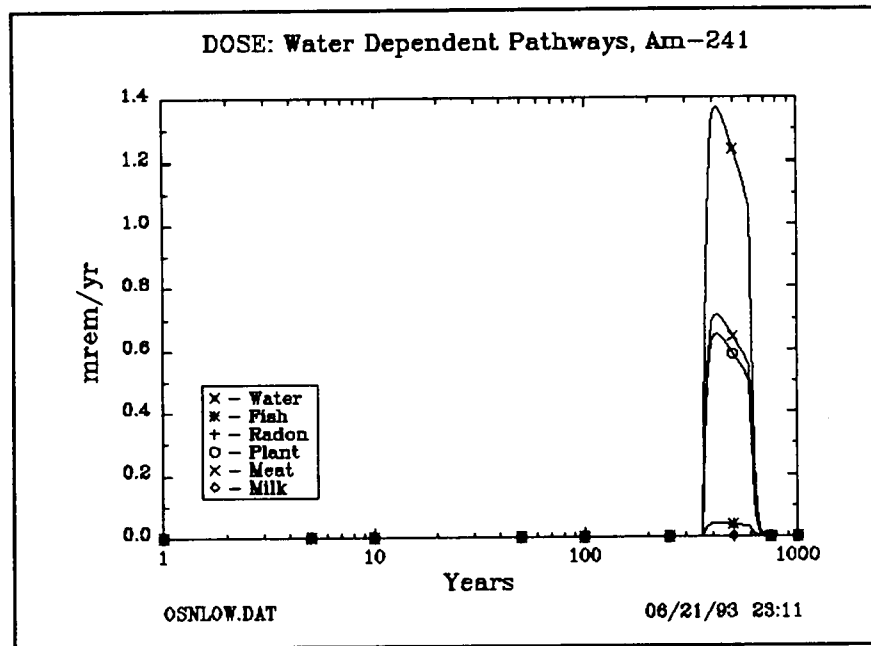


Figure 5.36. Dose From Am-241, Water-Dependent Pathways, Low K_d Value

5.3 Southern Off-Site Contaminated Area

5.3.1 Nominal Distribution Coefficients

The total dose to the receptor for the southern off-site area is shown in Fig. 5.37. Unlike the on-site and northern off-site contaminated areas, the dose to the receptor consists of two peaks. The first peak reaches a maximum dose of 0.55 mrem/yr at time zero and slowly decays over an approximate 270-year period. The second peak reaches a maximum dose of 2.7 mrem/yr at approximately 350 years (2340). The second peak slowly decays until about 1,000 years (2990). Figures 5.38, 5.39, and 5.40 illustrate the respective contributions to the total dose. Am-241 contributes approximately 0.1 mrem/yr (15% of the total dose) to the first peak and 2.6 mrem/yr (96% of the total dose) to the second peak. Pu-239 contributes approximately 0.44 mrem/yr (80% of the total dose) to the first peak and 0.1 mrem/yr (4% of the total dose) to the second peak. Finally, Pu-240 contributes approximately 0.027 mrem/yr (5% of the total dose) to the first peak and a negligible amount to the second.

Figures 5.41, 5.42, and 5.43 show the dose for each radionuclide summed over water-independent and water-dependent pathways. The dose for each of the radionuclides summed over all pathways for the first peak is the result of water-independent pathways, and the dose for the second peak is the result of water-dependent pathways. The peaks are somewhat overlapping.

Figures 5.44, 5.45, and 5.46 illustrate the dose received by individual water-independent pathways from the first peak for Am-241, Pu-239, and Pu-240, respectively. As for the on-site and northern off-site areas, dust inhalation and soil ingestion produce the highest dose. Soil ingestion contributes approximately 0.24 mrem/yr (43% of the total dose), and dust inhalation contributes approximately 0.24 mrem/yr (43% of the total

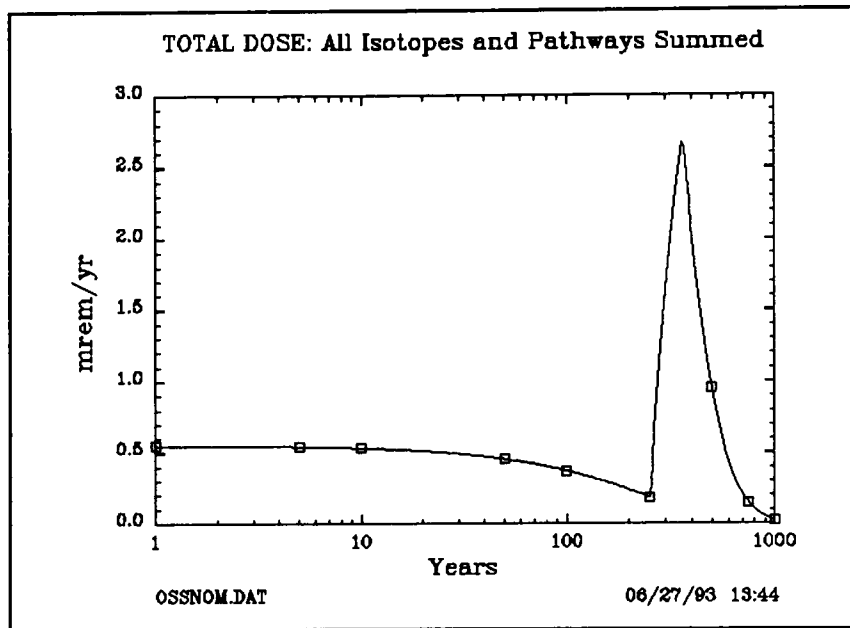


Figure 5.37. Total Dose From the Southern Off-Site Area, All Isotopes and Pathways Summed

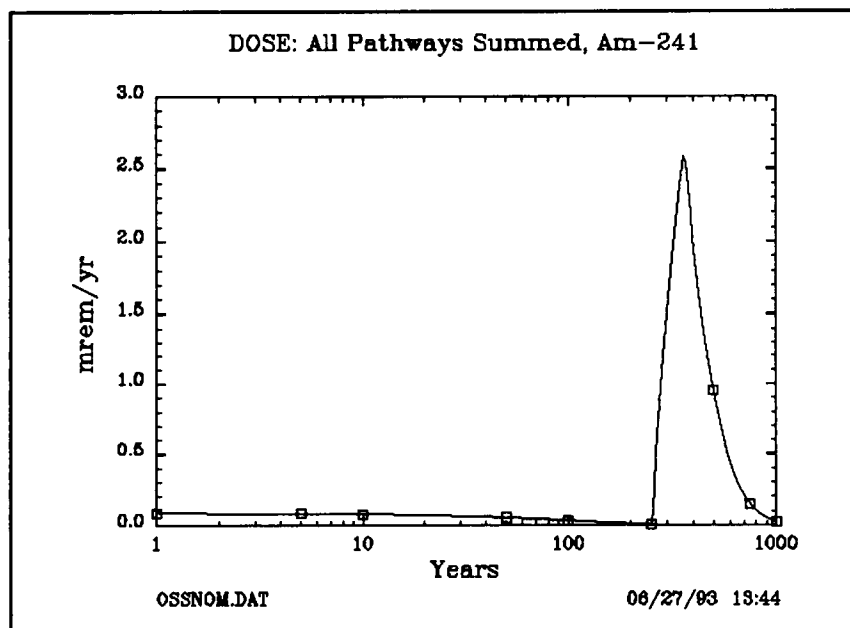


Figure 5.38. Dose From Am-241, Summed Over All Pathways

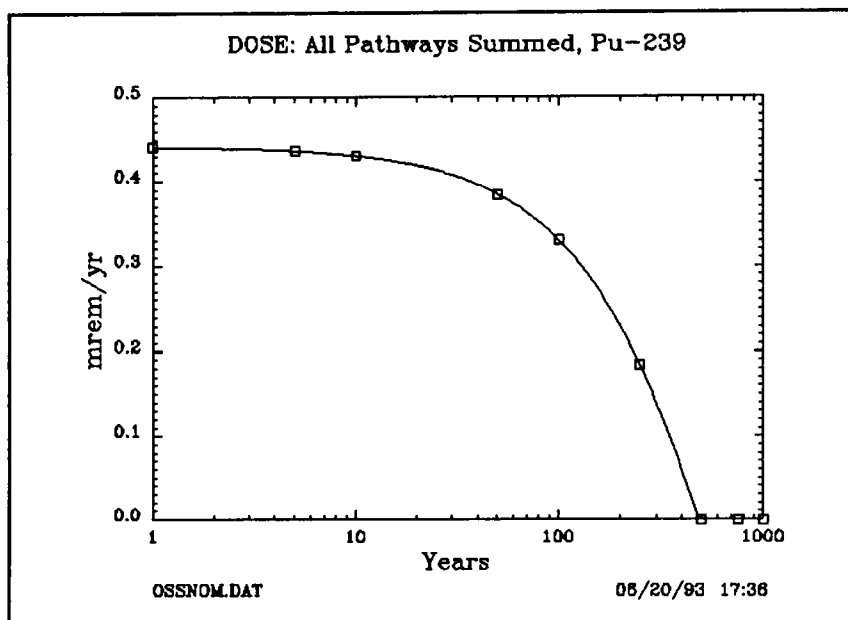


Figure 5-39. Dose From Pu-239, Summed Over All Pathways

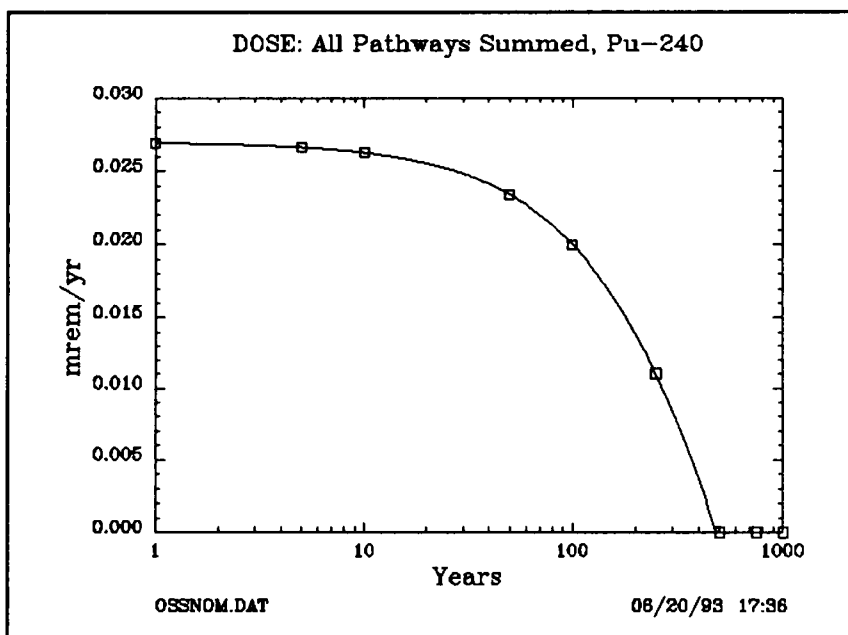


Figure 5.40. Dose From Pu-240, Summed Over All Pathways

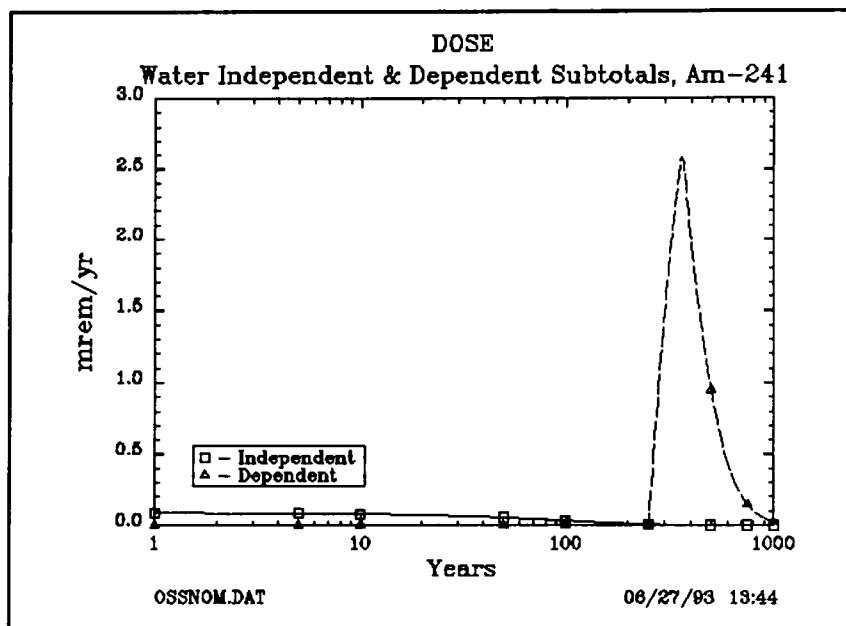


Figure 5.41. Dose From Am-241, Summed Over Water-Independent and Water-Dependent Pathways

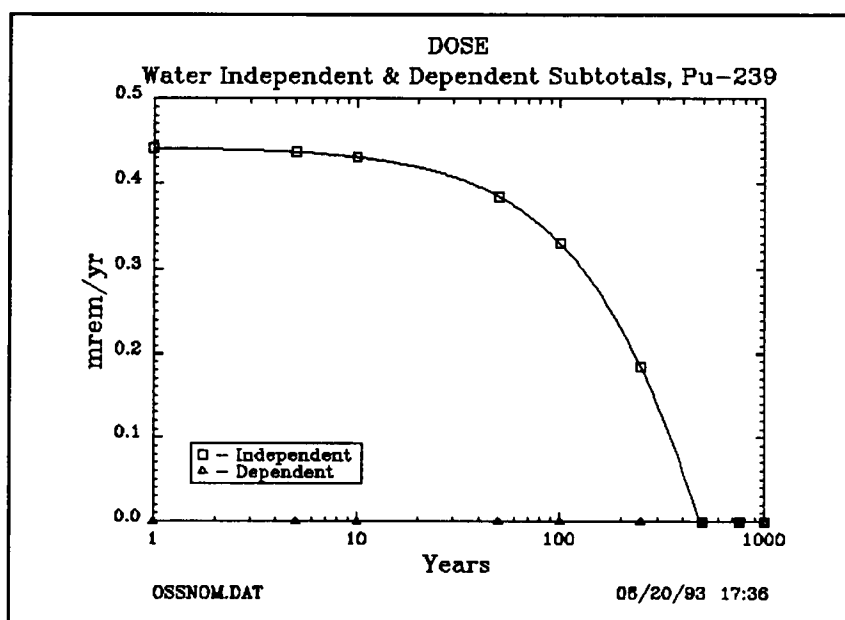


Figure 5.42. Dose From Pu-239, Summed Over Water-Independent and Water-Dependent Pathways

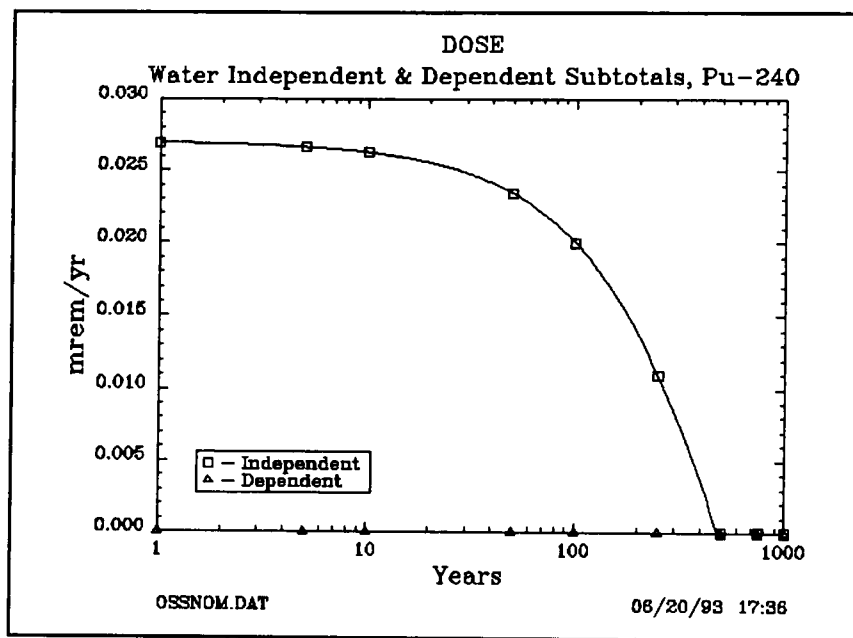


Figure 5.43. Dose From Pu-240, Summed Over Water-Independent and Water-Dependent Pathways

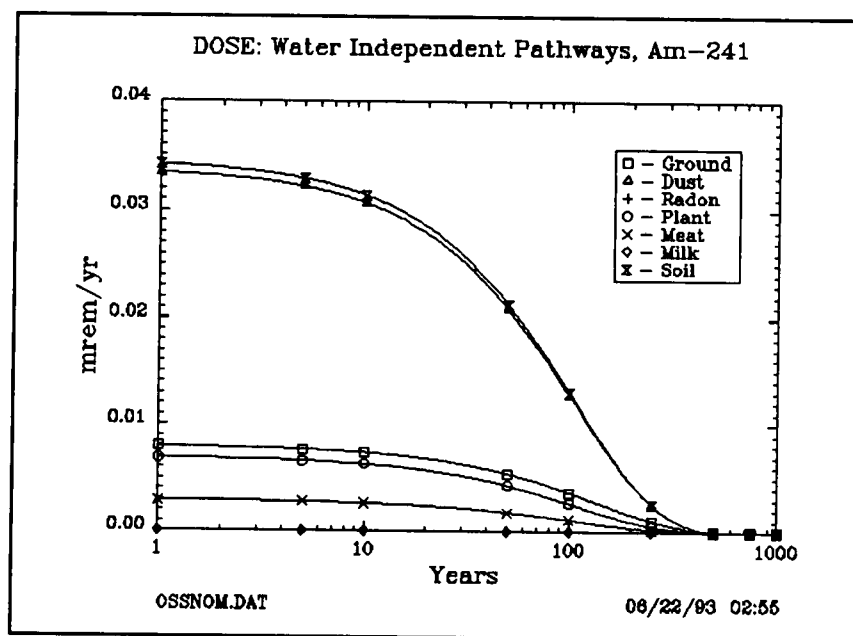


Figure 5.44. Dose From Am-241, Water-Independent Pathways

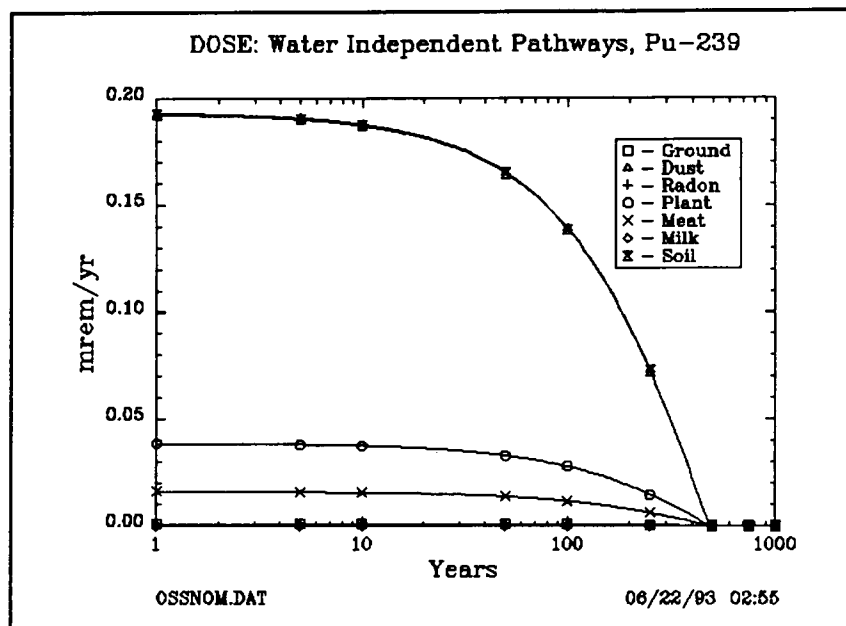


Figure 5.45. Dose From Pu-239, Water-Independent Pathways

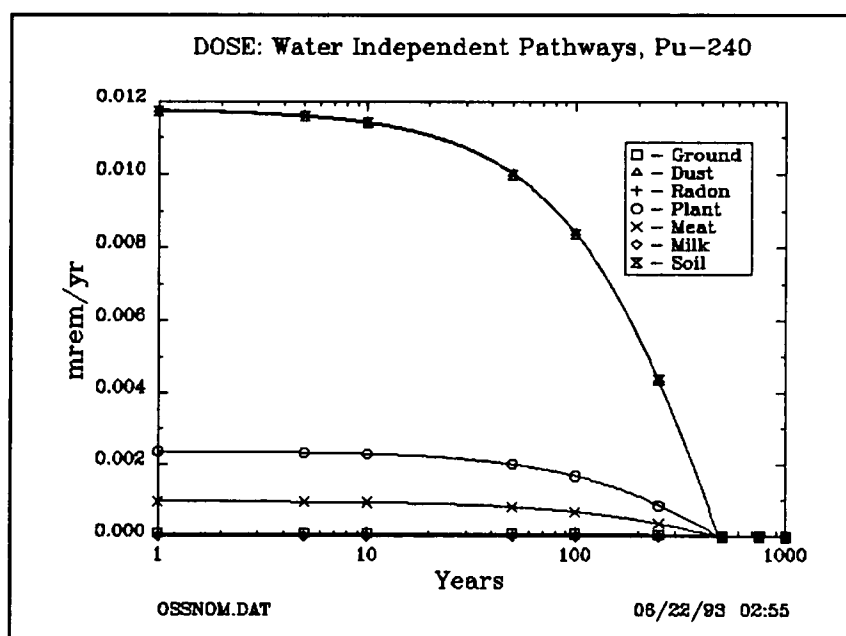


Figure 5.46. Dose From Pu-240, Water-Independent Pathways

dose.) Plant ingestion contributes approximately 0.048 mrem/yr (8.6% of the total dose), and meat ingestion contributes approximately 0.020 mrem/yr (3.6% of the total dose). Direct ground radiation produces only 0.0088 mrem/yr (1.6% of the total dose). Milk ingestion contributes an extremely small dose of 1.4×10^{-6} mrem/yr (essentially 0% of the total dose).

Figure 5.47 illustrates the dose received by individual water-dependent pathways from the second peak for Am-241. Drinking-water ingestion contributes approximately 0.37 mrem/yr (50% of the total dose). Plant and meat ingestion contribute approximately 0.18 mrem/yr (24% of the total dose) and 0.19 mrem/yr (26% of the total dose), respectively. The remaining dose is produced by fish and milk ingestion. Fish ingestion contributes 0.0028 mrem/yr (0.4% of the total dose), and milk ingestion contributes 0.00011 mrem/yr (0.02% of the total dose).

5.3.2 High Distribution Coefficients

The high distribution coefficient value for both Pu and Am is $2000 \text{ cm}^3/\text{g}$. These distribution coefficients produce a different dose to the receptor than that for the nominal case. Only one dose peak, for water-independent pathways, occurs. This peak is exactly the same as the one for the nominal distribution coefficients as shown in Fig. 5.37. Thus, an increase in the distribution coefficient from the nominal value causes a decrease in the dose received from water-dependent pathways.

5.3.3 Low Distribution Coefficients

The low distribution coefficient values for Pu and Am are $550 \text{ cm}^3/\text{g}$ and $20 \text{ cm}^3/\text{g}$, respectively. These distribution coefficients produce a significantly larger dose to the receptor than that for the nominal case. The total dose to the receptor is shown in Fig. 5.48. Unlike the dose for the nominal distribution coefficients, this dose consists of

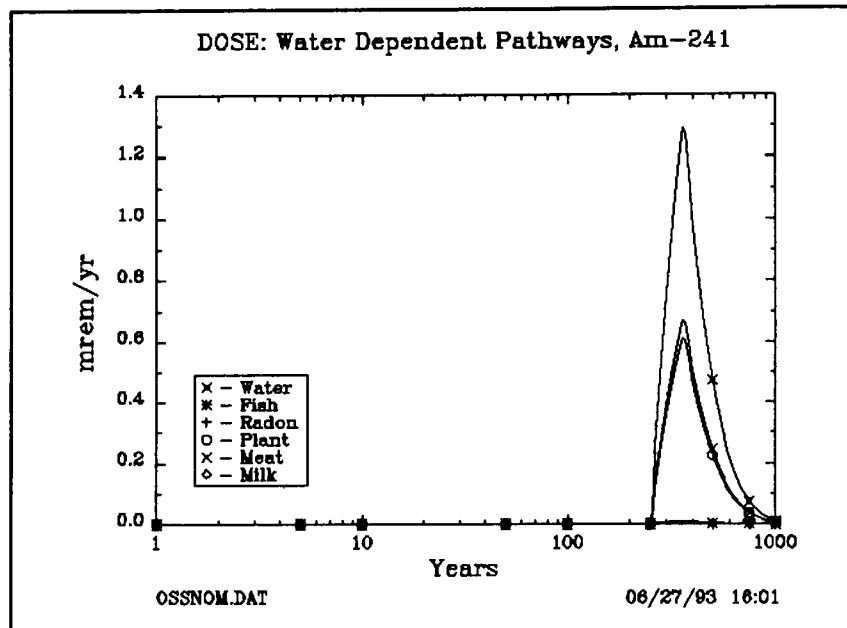


Figure 5.47. Dose From Am-241, Water-Dependent Pathways

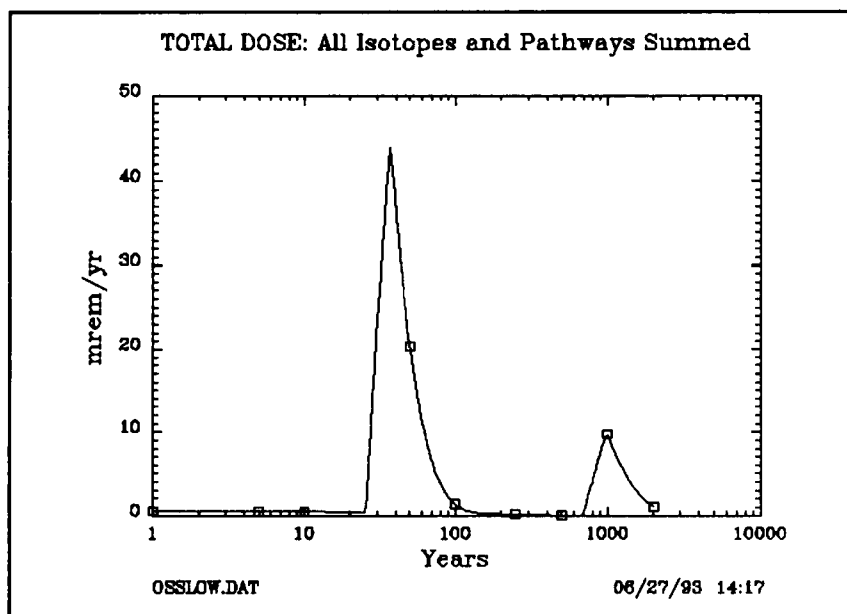


Figure 5.48. Total Dose From Southern Off-Site Area, All Isotopes and Pathways Summed, Low K_d Value

three peaks. The first peak is identical to that shown in Fig. 5.37. The second is similar to the second peak in Fig. 5.37 except that the dose is much larger. The third peak follows the second several hundred years later and is the result of Pu-239 and Pu-240 from water-dependent pathways. It produces 10 mrem/yr at approximately 1,000 yrs (2990).

Figures 5.49, 5.50, and 5.51 illustrate the contributions by Am-241, Pu-239, and Pu-240 to the total dose. The contributions to the first peak are identical to that for the nominal and high distribution coefficient values. Am-241 contributes 44 mrem/yr (about 100% of the total dose) to the second peak. Pu-239 contributes approximately 9.5 mrem/yr (95% of the total dose) to the third peak, and Pu-240 contributes approximately 0.5 mrem/yr (5% of the total dose).

Figures 5.52, 5.53, and 5.54 illustrate the contributions from Am-241, Pu-239, and Pu-240 summed over water-independent and water-dependent pathways. As for the nominal case, the dose for the first peak results completely from water-independent pathways, and the dose for the second and third peaks result completely from water-dependent pathways.

Figures 5.55, 5.56, and 5.57 illustrate the contributions from individual water-independent pathways for Am-241, Pu-239, and Pu-240. The contributions match those for the nominal and high-distribution coefficient cases. Figures 5.58, 5.59, and 5.60 illustrate the contributions from water-dependent pathways for Am-241, Pu-239, and Pu-240. For the second peak, drinking-water ingestion produces the highest dose, approximately 22 mrem/yr (50% of the total dose) at 37 years (2027). Plant ingestion produces approximately 10 mrem/yr (23% of the total dose), and meat ingestion produces approximately 11 mrem/yr (26% of the total dose). The dose from fish and milk is negligible (about 0.02% of the total dose).

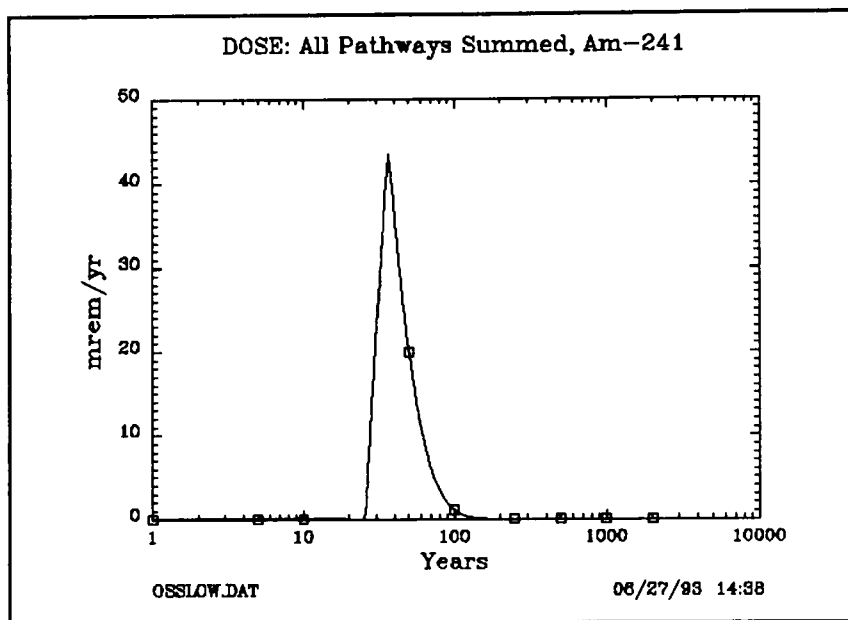


Figure 5.49. Dose From Am-241, Summed Over All Pathways, Low K_d Value

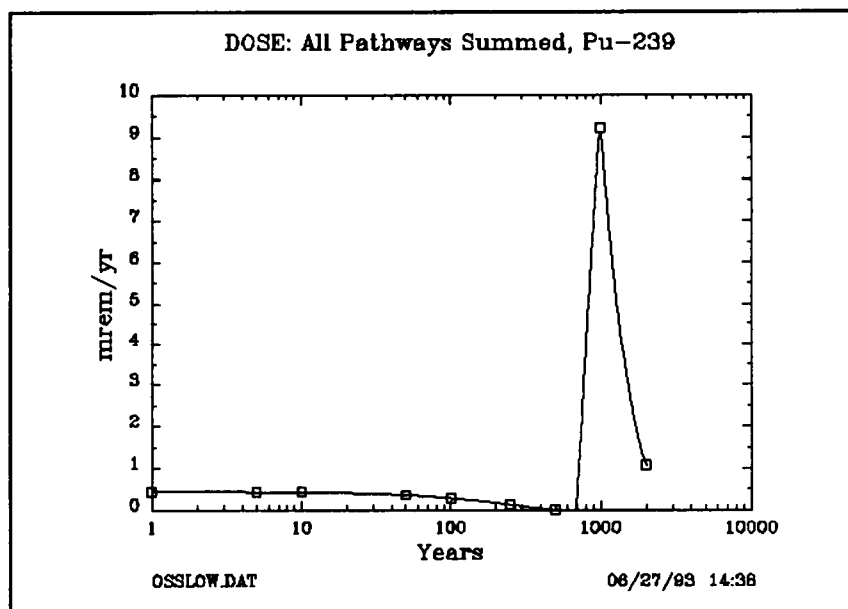


Figure 5.50. Dose From Pu-239, Summed Over All Pathways, Low K_d Value

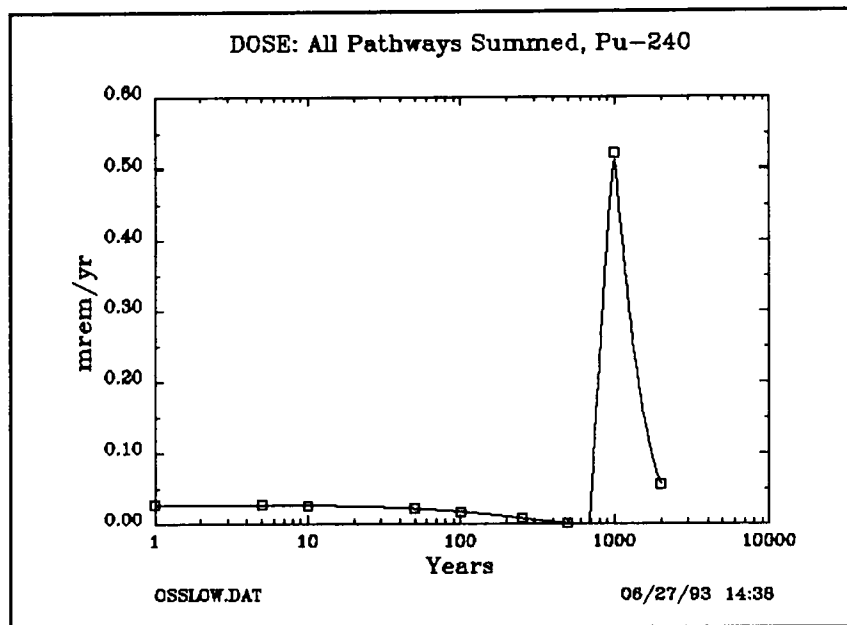


Figure 5.51. Dose From Pu-240, Summed Over All Pathways, Low K_d Value

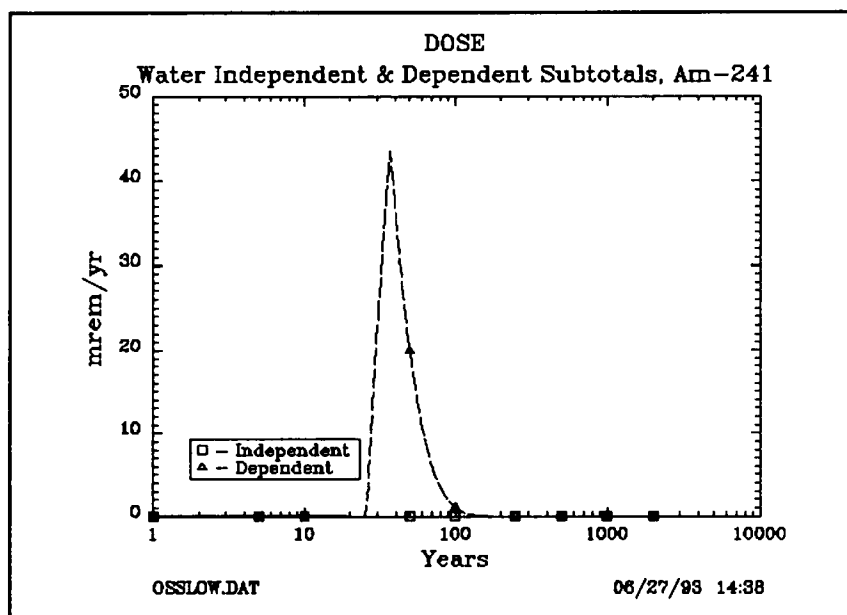


Figure 5.52. Dose From Am-241 Dose, Summed Over Water-Independent and Water-Dependent Pathways, Low K_d Value

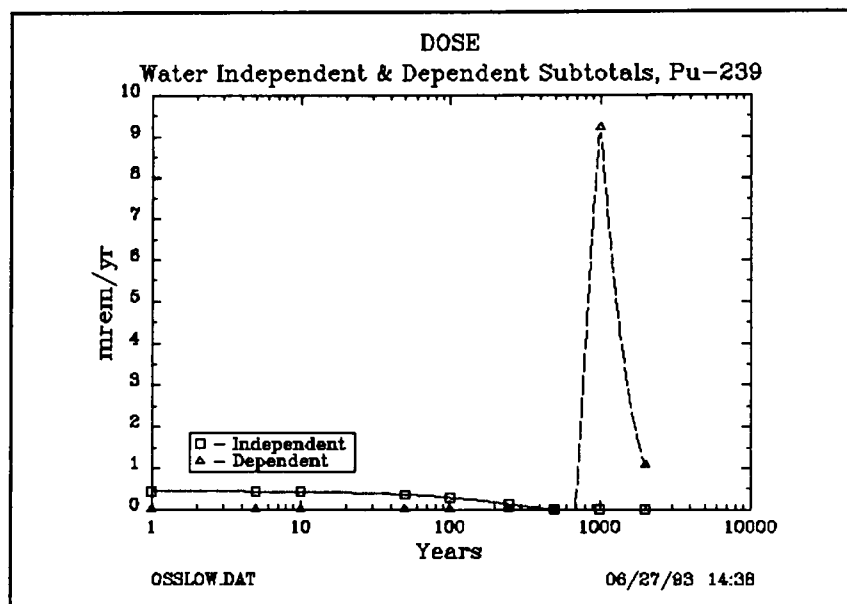


Figure 5.53. Dose From Pu-239, Summed Over Water-Independent and Water-Dependent Pathways, Low K_d Value

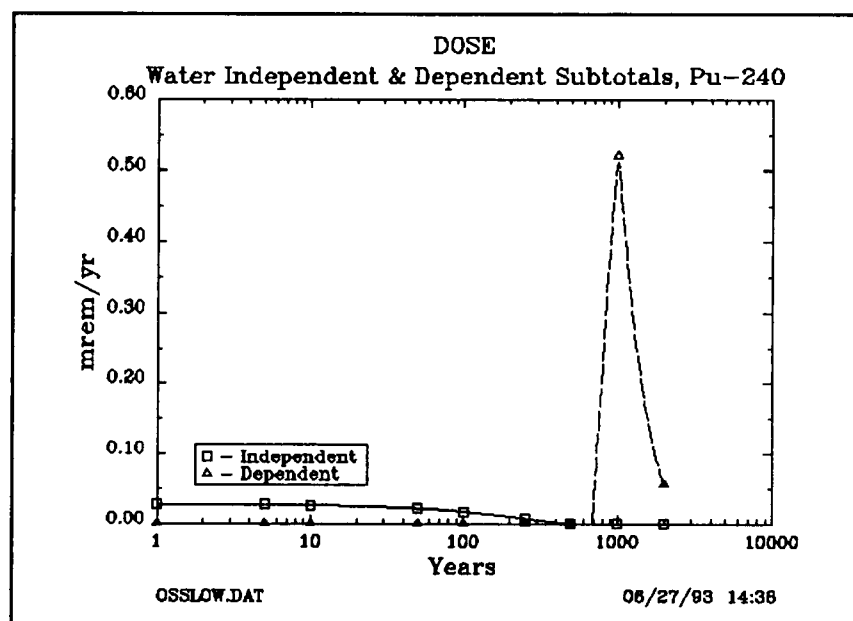


Figure 5.54. Dose From Pu-240, Summed Over Water-Independent and Water-Dependent Pathways, Low K_d Value

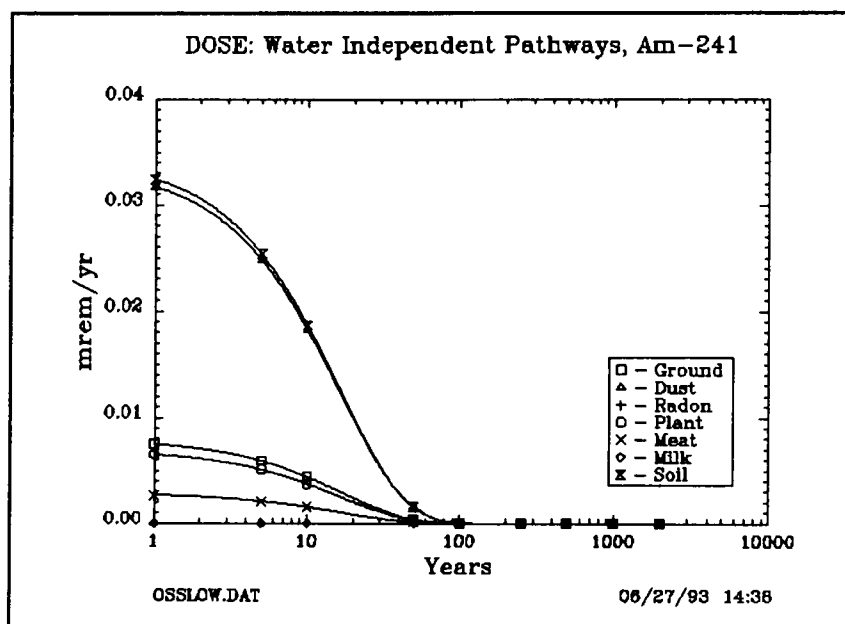


Figure 5.55. Dose From Am-241, Water-Independent Pathways, Low K_d Value

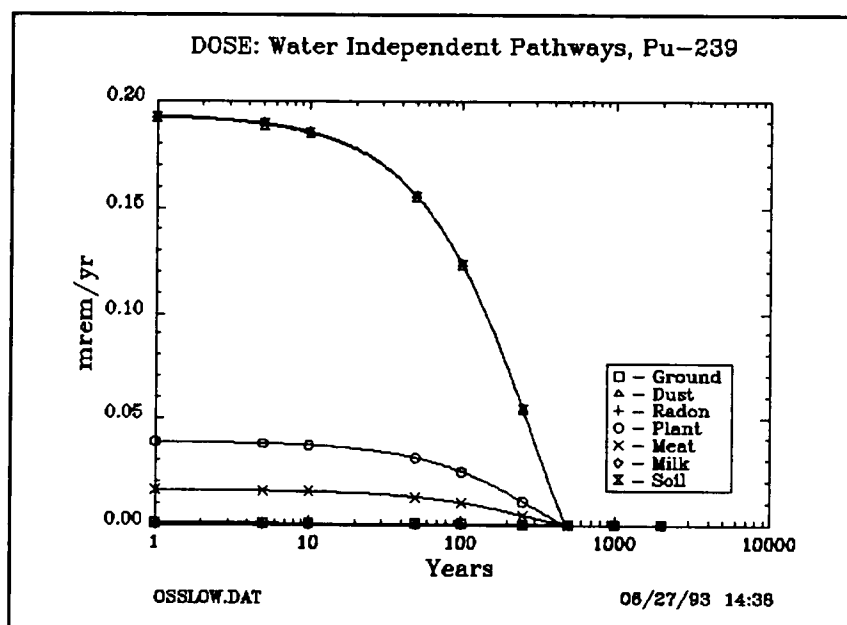


Figure 5.56. Dose From Pu-239, Water-Independent Pathways, Low K_d Value

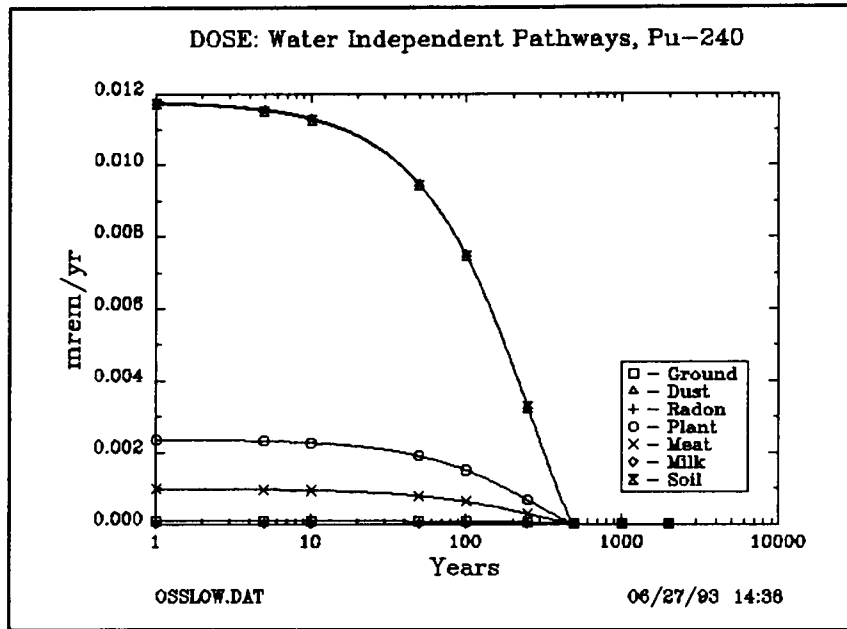


Figure 5.57. Dose From Pu-240, Water-Independent Pathways, Low K_d Value

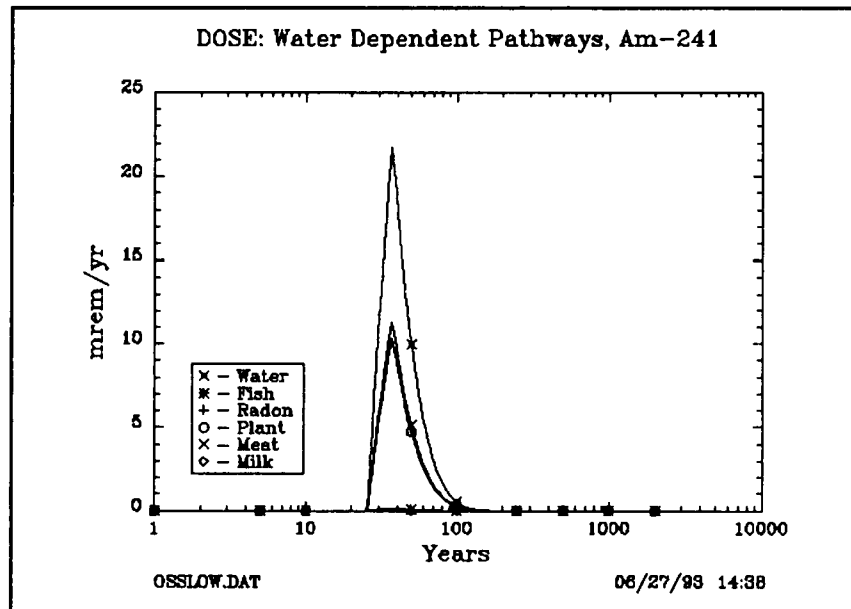


Figure 5.58. Dose From Am-241, Water-Dependent Pathways, Low K_d Value

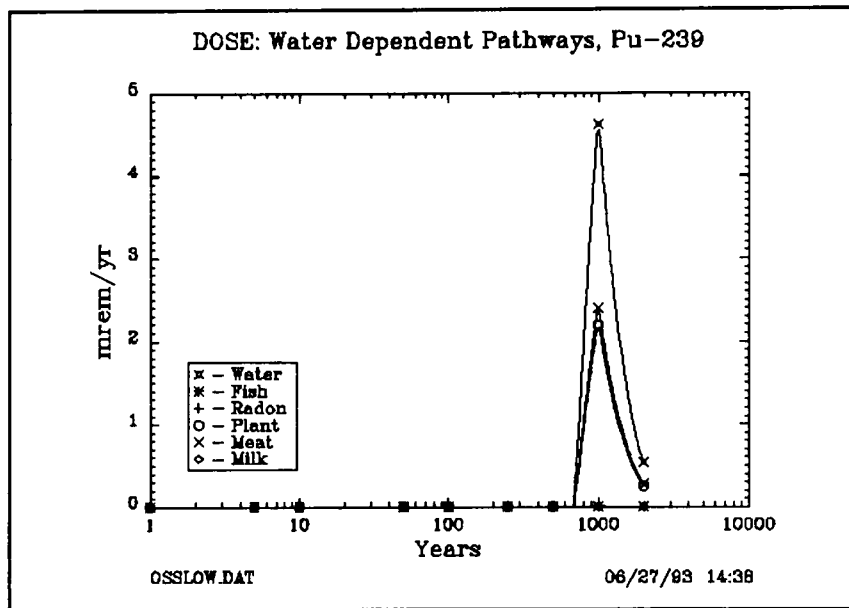


Figure 5.59. Dose From Pu-239, Water-Dependent Pathways, Low K_d Value

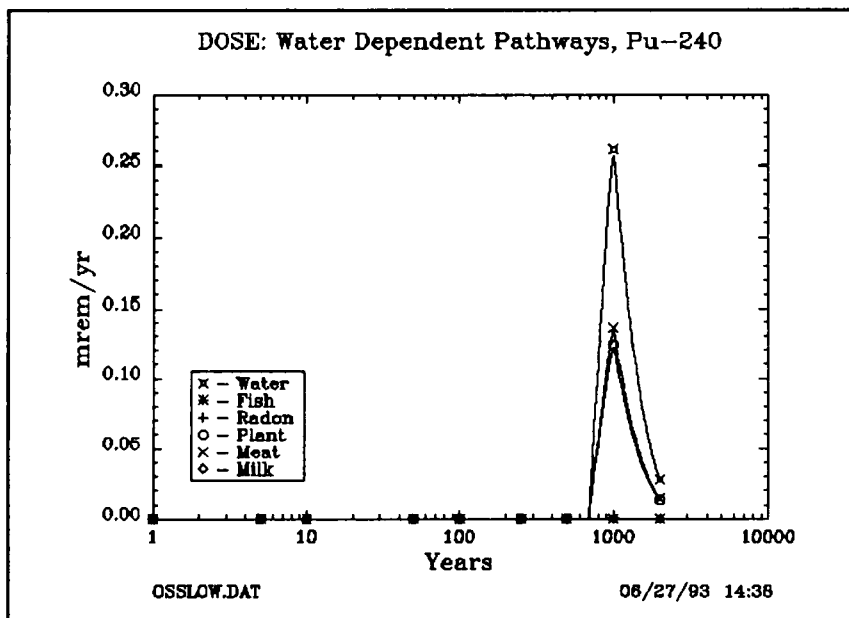


Figure 5.60. Dose From Pu-240, Water-Dependent Pathways, Low K_d Value

For the third peak, the contributions from the various pathways are fractionally the same as that for the second peak. Drinking-water ingestion produces the highest dose, approximately 4.9 mrem/yr (50% of the total dose). Plant and meat ingestion contribute most of the remaining dose. Plant ingestion produces approximately 2.3 mrem/yr (24% of the total dose), and meat ingestion produces approximately 2.5 mrem/yr (26% of the total dose). The dose from fish and milk is negligible.

6. SENSITIVITY ANALYSIS

A sensitivity analysis of some of the input parameters for the on-site area was performed. As with any predictive model, the accuracy of the predictions depends on the accuracy of the input parameters. Parameters with high sensitivities will have a greater effect on the predicted results. Therefore, these parameters should be determined more accurately.

The most sensitive parameter in the model is the distribution coefficient, K_d , for americium and plutonium. Because K_d is so sensitive, the analysis is divided into two sections: one for the nominal and high distribution coefficients, and the other for the low distribution coefficients. The results of the sensitivity analysis are presented in Table 6.1.

For the nominal and high distribution coefficients, only five parameters are significant (increases or decreases of more than 1%). The fruits, vegetables, and grain consumption rate and the soil ingestion consumption rate are the only significant ingestion parameters. The maximum value for the fruits, vegetables, and grain consumption rate increases the dose by 4% and the maximum value for the soil ingestion consumption rate increases the dose by 8.3%. The inhalation rate, the dilution length, and the soil mass loading, which affect the dose from the dose inhalation pathway, are the other three parameters. The maximum value for the inhalation rate increases the dose by 6%. The maximum value for the dilution length decreases the dose by 13%, and the minimum value increases the dose by 0.1%. Lastly, the maximum value for the soil mass loading increases the dose by 175%, and the minimum value decreases the dose by 39%. Clearly, the soil mass loading is the most sensitive parameter.

For the low distribution coefficient, many of the parameters are sensitive. Fourteen parameters increase or decrease by more than 1%. Ten of these parameters are

Table 6.1. Sensitivity of On-Site Contaminated Area Parameters

Parameter	Value		Nominal and High Distribution Coefficient Cases		Low Distribution Coefficient Cases	
	High/Low		Dose (mRem/yr)	Percentage Increase or Decrease from Nominal Value	Dose (mRem/yr)	Percentage Increase or Decrease from Nominal Value
Fruits, Vegetables, and Grain Consumption Rate (kg/yr)	300		62	+4%	455	+7.8%
	-		-	-	-	-
Leafy Vegetables Consumption (kg/yr)	45		60.3	+0.6%	443	+5.0%
	-		-	-	-	-
Milk Consumption (L/yr)	200		60	+0%	422	+0%
	92		60	+0%	422	+0%
Meat and Poultry Consumption (kg/yr)	110		60.3	+0.5%	439	+4.0%
	-		-	-	-	-
Fish Consumption (kg/yr)	21		60	+0%	423	+2.4%
	-		-	-	-	-
Other Aquatic Consumption (kg/yr)	5		60	+0%	434	+2.8%
	-		-	-	-	-

Table 6.1. Sensitivity of On-Site Area Parameters (continued)

Parameter	Value	Nominal and High Distribution Coefficient Cases		Low Distribution Coefficient Cases	
		Dose (mRem/yr)	Percentage Increase or Decrease from Nominal Value	Dose (mRem/yr)	Percentage Increase or Decrease from Nominal Value
Soil Ingestion (g/yr)	43.8	65	+8.3%	422	+0%
Drinking Water Consumption (L/yr)	730	60	+0%	512	+21%
Fraction of Drinking Water from Site (dimensionless)	-	-	-	-	-
Fraction of Aquatic Food from Site (dimensionless)	0.5	60	+0%	318	-33%
Drinking Water Fraction From Ground Water (dimensionless)	1.0	60	+0%	426	+0.8%
Livestock Water Fraction From Ground Water (dimensionless)	-	-	-	-	-
	-	-	-	-	-
	0.5	60	+0%	319	-32%
	-	-	-	-	-
	0.5	60	+0%	417	-1.2%

Table 6.1. Sensitivity of On-Site Area Parameters (continued)

Parameter	Value	Nominal and High Distribution Coefficient Cases			Low Distribution Coefficient Cases		
		High/Low	Dose (mRem/yr)	Percentage Increase or Decrease from Nominal Value	Dose (mRem/yr)	Percentage Increase or Decrease from Nominal Value	
Irrigation Fraction From Ground Water (dimensionless)	-		-	-	-	-	-
	0.5		60	+0%	325	-30%	
Inhalation Rate (kg/yr)	10,000		63.6	+6%	422	+0%	
	-		-	-	-	-	-
Total and Effective Porosity (dimensionless)	0.46 and 0.43		60	+0%	305	-38%	
	0.24 and 0.13		60	+0%	676	+60%	
Hydraulic Conductivity (dimensionless)	32		60	+0%	422	+0%	
	0.32		60	+0%	422	+0%	
Evapotranspiration Coefficient (dimensionless)	0.9		60	+0%	242	-74%	
	0.7		60	+0%	511	+21%	
Runoff Coefficient (dimensionless)	0.3		60	+0%	414	-2%	
	0.1		60	+0%	430	+2%	

Table 6.1. Sensitivity of On-Site Area Parameters (continued)

Parameter	Value		Nominal and High Distribution Coefficient Cases		Low Distribution Coefficient Cases	
	High/Low		Dose (mRem/yr)	Percentage Increase or Decrease from Nominal Value	Dose (mRem/yr)	Percentage Increase or Decrease from Nominal Value
Well Pump Intake Depth (m)	-	-	-	-	-	-
	0.5	60	60	+0%	1464	+247%
Contaminated Zone Erosion Rate (m/yr)	0.00047	60	60	0%	420	-0.5%
	0.00015	60	60	0%	425	+0.7%
Dilution Length (dimensionless)	250	53	53	-13%	422	+0%
	0.03	60.1	60.1	+0.1%	422	+0%
Soil Mass Loading (g/m ³)	0.0002	165	165	+175%	425	+0.6%
	0.0000209	43.2	43.2	-39%	422	+0%

dietary or nondietary ingestion parameters. The other four are hydrological parameters. The most sensitive of these parameters are the evapotranspiration coefficient, the well pump intake depth, total and effective porosities, the fraction of drinking water from site, the drinking water fraction from groundwater, and the irrigation fraction from groundwater. All of these parameters increase or decrease the dose 30% or more. The most sensitive parameter is the well pump intake depth; the minimum value increases the dose by 247%. The minimum values of the total and effective porosities increase the dose by 60%, and the maximum values of the total and effective porosities decrease the dose by 38%. The maximum value of the evapotranspiration coefficient decreases the dose by 74%, and the minimum value increases the dose by 21%.

Best- and worst-case scenarios have been created from the results of the sensitivity analysis. The best-case scenario has high distribution coefficients. The values of the parameters in the sensitivity analysis that decrease the dose are also selected. The best-case scenario for the on-site, northern off-site, and southern off-site contaminated areas predict doses of 41 mrem/yr, 0.47 mrem/yr, and 0.37 mrem/yr, respectively. It represents a decrease in dose of 46%, 45%, and 630% (nominal/high distribution coefficients), respectively. The total dose for the on-site, northern off-site, and southern off-site contaminated areas under best-case scenario conditions is illustrated in Figs. 6.1, 6.2, and 6.3, respectively.

The worst-case scenario has low distribution coefficients. The values of the parameters in the sensitivity analysis that increase the dose are also selected. The worst-case scenario for the on-site, northern off-site, and southern off-site contaminated areas predict doses of 3670 mrem/yr, 43 mrem/yr, and 85 mrem/yr, respectively. It represents an increase in dose of 870%, 1,400%, and 93% (low distribution coefficients), respectively.

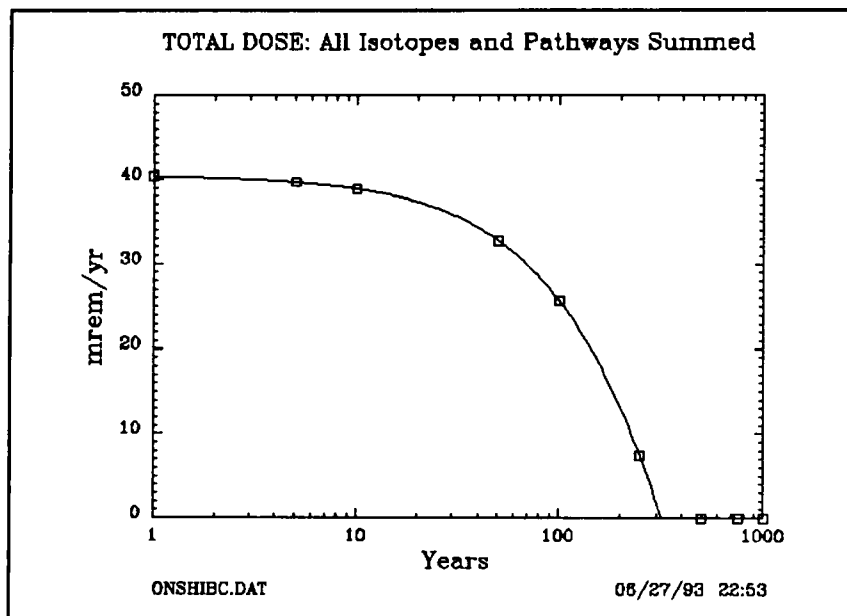


Figure 6.1. Total Dose for the On-Site Area, Best Case Scenario

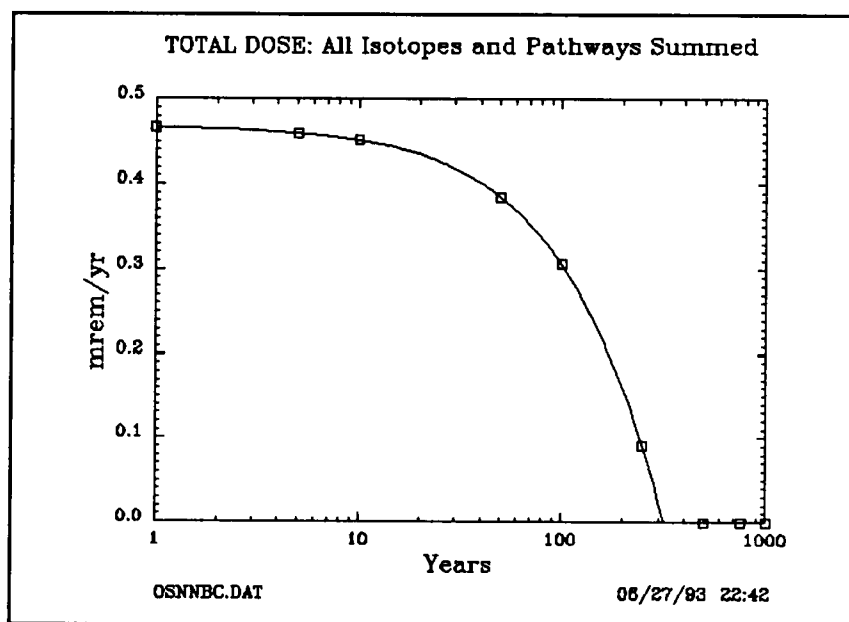


Figure 6.2. Total Dose for the Northern Off-Site Area, Best Case Scenario

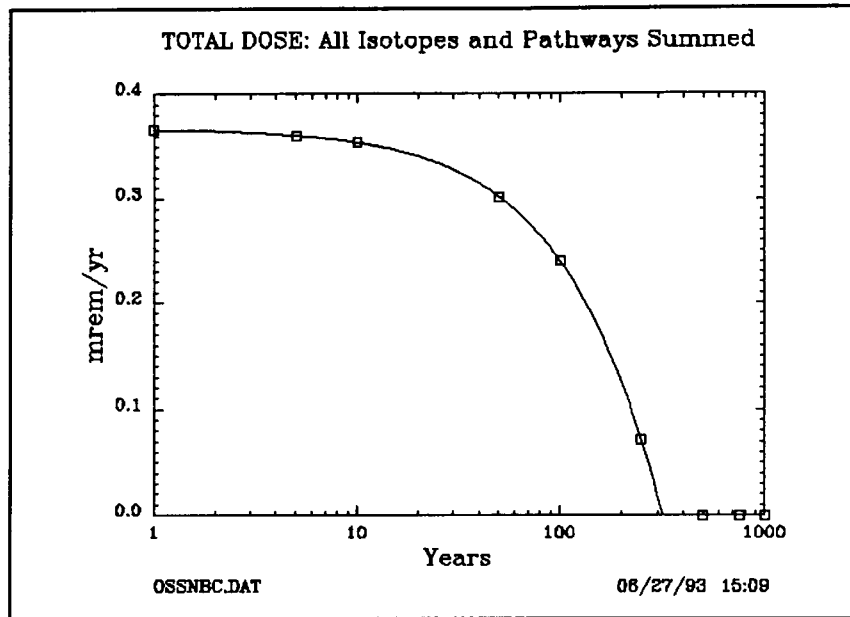


Figure 6.3. Total Dose for the Southern Off-Site Area, Best Case Scenario

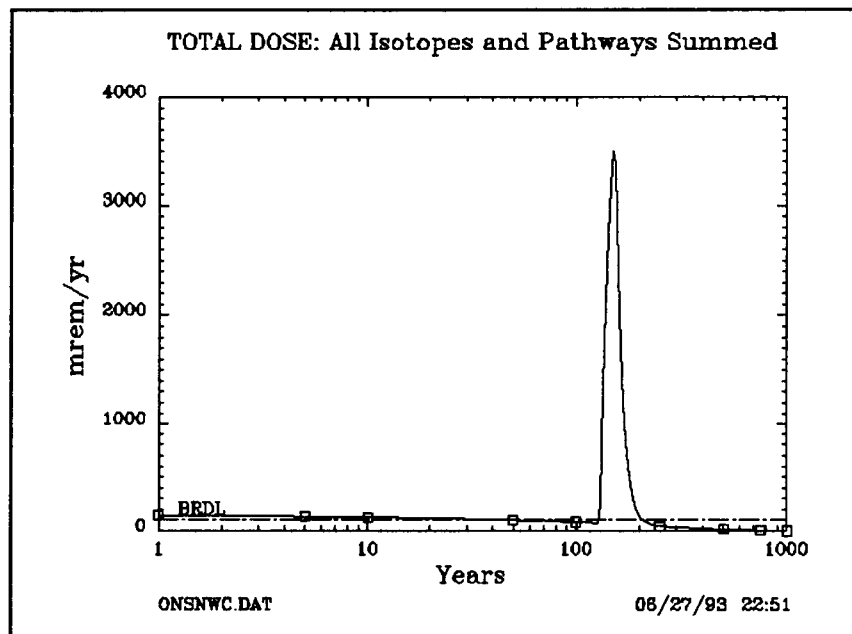


Figure 6.4. Total Dose for the On-Site Area, Worst Case Scenario

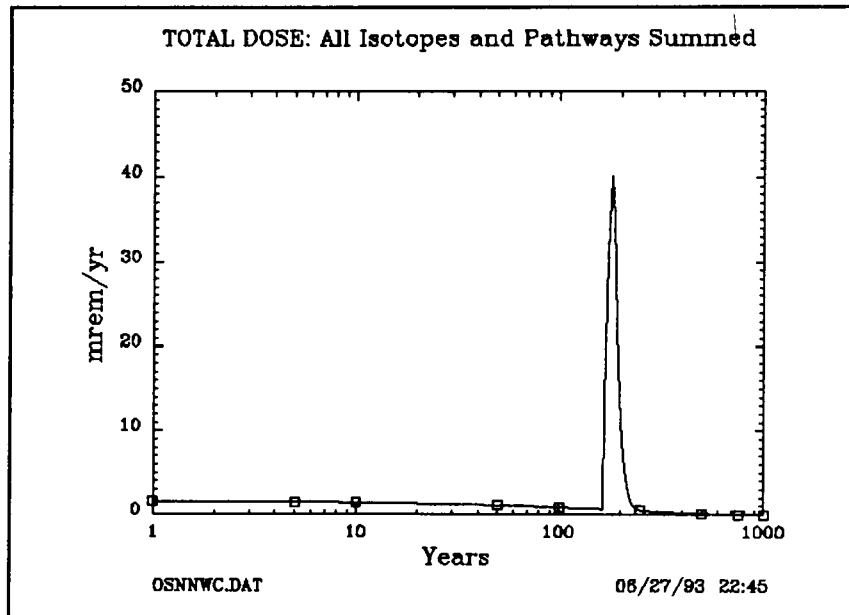


Figure 6.5. Total Dose for the Northern Off-Site Area, Worst Case Scenario

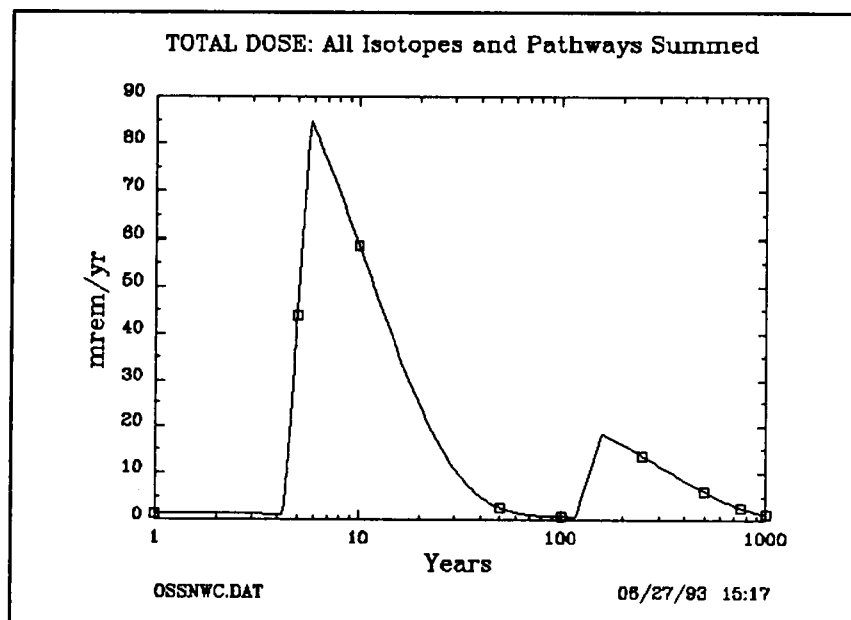


Figure 6.6. Total Dose for the Southern Off-Site Area, Worst Case Scenario

The total dose for the on-site, northern off-site, and southern off-site contaminated areas under worst-case scenario conditions is illustrated in Figs. 6.4, 6.5, and 6.6, respectively.

7. CONCLUSIONS

The soil at OU 2 and the soil, sediments, and surface water at OU 3 are contaminated by radionuclides. Significant concentrations of americium and plutonium are present in the soils at OU 2, as are less significant concentrations in the soils and sediments at OU 3. Very low concentrations of radionuclides are present in the surface water in OU 3. However, radionuclide contamination of the ground water at OU2 is inconclusive with the data from the Phase I RFI/RI borehole sampling study and contamination of the ground water in OU 3 is not expected.

Because DOE has both a commitment and a responsibility to protect the public and environment from undue risk from radiation exposure, these two OUs must be assessed to determine the risk to the public before their release from radiological control. The on-site contaminated area is located in OU 2 and is defined by the 1990 In Situ Survey. The northern and southern off-site areas are located in OU 3 and are defined by the boundaries of the Two Remedy Acreages.

As stated in the Introduction, this radiological assessment is intended to be a preliminary scoping model. The goals of this model are (1) determine the primary pathways for exposure (2) determine the critical and/or sensitive data parameters (3) estimate the effective dose equivalent to the receptor in the hypothetical scenario and based on the results assess the need for remediation under DOE Order 5400.5, and (4) estimate the radionuclide soil guideline if remediation is necessary.

This chapter contains the conclusions of these four goals based on the results and sensitivity analysis presented in Chapters 5 and 6. These results are based on the procedures and requirements of DOE Order 5400.5 and the methods of DOE/CH/8901.

Only Am-241, Pu-239, and Pu-240 are assessed. The other isotopes of plutonium

(Pu-238, Pu-241, and Pu-242) and the other radionuclides are not assessed because of their low concentrations.

7.1 PATHWAYS

The assessment is based on a family-farm land use scenario. This scenario assumes that the receptors may receive a radiation dose from nine pathways. These nine pathways are: (1) direct radiation from radionuclides in the soil, (2) inhalation of resuspended dust (if the contaminated area is exposed at the ground surface), (3) inhalation of radon decay products, (4) ingestion of food from crops grown in the contaminated soil, (5) ingestion of milk from livestock raised in the contaminated area, (6) ingestion of meat from livestock raised in the contaminated area, (7) ingestion of fish from a nearby pond contaminated by water percolating through the contaminated zone, (8) ingestion of water from a well contaminated by water percolating through the contaminated zone, and (9) ingestion of contaminated soil.

The three most significant pathways (contributing 45% or more of the total dose) for all three areas are dust inhalation, soil ingestion, and drinking-water ingestion. Dust inhalation and soil ingestion produce 95% of the dose when the distribution coefficients are high and the water-independent pathways are the dominant source. Drinking water ingestion produces 50% of the dose when the distribution coefficients are low and the water-dependent pathways are the dominant source. Less significant, plant and meat ingestion pathways produce about 25% of the dose for the water-dependent dose peaks. All three of these water-dependent pathways require that the radionuclides in soil leach into the groundwater before either water or wind erosion remove them from the source.

Plant, meat, and direct gamma radiation produce a small amount of the dose for water-independent dose peaks. The fish and milk pathways produce a negligible amount

of dose. For the fish pathway this is explained by the large amount of dilution of contaminated water in the nearby water bodies. For the milk pathway this is explained by the extremely poor milk transfer factors. The radon pathway produces no significant dose in any of the three areas.

7.2 DATA REQUIREMENTS

The most sensitive parameter in the assessment is the distribution coefficient, K_d , for americium and plutonium. Because the drinking-water, plant, and meat ingestion (water-dependent) pathways require that the radionuclides in soil leach into the groundwater before a dose can be produced, high values ensure that no significant amount of Am-241 is leached into the groundwater. Consequently, for nominal and high values, the water-independent pathways are the dominant source of dose (except for the southern off-site area where the surficial material is shallow enough to allow significant leaching). As the distribution coefficient for Am-241 decreases and more Am-241 is leached into the groundwater, the water-dependent pathways become more significant. For the lowest value, 20 cm³/g, water-dependent pathways are the dominant source of dose. Thus, for future assessments of these contaminated areas at RFP, it is vitally important that the distribution coefficient be determined for each contaminated area.

For sites with average or higher distribution coefficients (except for the southern contaminated area where the surficial material is shallow enough to allow significant leaching for nominal distribution coefficients) the water-independent pathways of dust inhalation and soil ingestion are dominant sources of the dose. Parameters that affect these pathways should be determined on a site-by-site basis. The dilution length, soil mass loading, soil ingestion rate, and inhalation rate significantly affect these two pathways. The soil ingestion rate and the inhalation rate are determined by scenario. For example,

the inhalation rate is influenced by the activity of the receptor. If the receptor is engaged in heavy labor, the inhalation rate will be high; if his activity is light, the inhalation rate will be light. The dilution length and soil mass loading should be measured at the site. However, the soil mass loading is often affected by the activities of the land use scenario. For example, tilling and vehicular traffic will increase the loading. So, the effect of scenario activities on the soil mass loading should also be taken into account.

7.3 REMEDIATION REQUIREMENTS

7.3.1 On-Site Contaminated Area

Because the distribution coefficient (K_d) has such an enormous effect on the dose to the receptor, five cases were considered for each of the areas. These are the nominal, high, low, best, and worst cases. The nominal case consists of all nominal parameters. The high and low cases consist of all nominal parameters except for the distribution coefficients which have either high or low values, respectively. The best case scenario consists of high distribution coefficient values and other parameter values which will tend to reduce the dose to the receptor. Finally, the worst case scenario consists of low distribution coefficients and other parameter values which will tend to increase the dose to the receptor. Table 7.1 summarizes the results for each of the cases.

The maximum dose to the receptor considering either the nominal or high case is 60 mrem/yr. This dose principally results from dust inhalation and soil ingestion. As the distribution coefficient for Am-241 decreases, the significance of water-dependent pathways increases. At a distribution coefficient of $20 \text{ cm}^3/\text{g}$ (low case) the dose from Am-241 produced through water-dependent pathways is about 422 mrem/yr, a 600% increase in the dose. The best- and worst-case scenarios predict doses of 41 mrem/yr (46% decrease) and 3,670 mrem/yr (6000% increase). The results of the nominal and high cases

Table 7.1. Dose to Receptor for Each of the Parameters Sets

Parameter Set	Dose (mrem/yr)	Increase over nominal set %
On-site Contaminated Area		
Nominal Kd, other parameters nominal	60	-
High Kd, other parameters nominal	60	0%
Low Kd, other parameters nominal	422	600%
Best case (high Kd, best case parameters)	41	-46%
Worst case (low Kd, worst case parameters)	3670	6000%
Northern Off-site Contaminated Area		
Nominal Kd, other parameters nominal	0.68	-
High Kd, other parameters nominal	0.68	0%
Low Kd, other parameters nominal	2.8	310%
Best case (high Kd, best case parameters)	0.47	-45%
Worst case (low Kd, worst case parameters)	43	6200%
Southern Off-site Contaminated Area		
Nominal Kd, other parameters nominal	2.7	-
High Kd, other parameters nominal	0.55	390%
Low Kd, other parameters nominal	44	1500%
Best case (high Kd, best case parameters)	0.37	-630%
Worst case (low Kd, worst case parameters)	85	3000%

indicate that the dose to the receptor in the on-site contaminated area does not exceed the requirements of DOE Order 5400.5. However, the results using the low case for Am-241 exceed the base radiological dose limit of 100 mrem/yr by a factor of four. The results using the worst-case scenario exceed the base radiological dose limit by a factor of 37. Thus, DOE Order 5400.5 may require that the on-site area be remediated before it can be released to the public. Further study of OU 2 is warranted.

The single radionuclide soil guideline for Am-241 ranges from 7.1 pCi/g for the low distribution coefficient to 0.83 pCi/g for the worst-case scenario. No single radionuclide soil guideline exists for Pu-239 or Pu-240 because the only dose peak that exceeds the base radiological dose limit is produced solely by Am-241. Reducing the soil concentrations of Am-241 to below the guideline will reduce the dose below the limit for the respective conditions.

7.3.2 Northern Off-Site Contaminated Area

The maximum dose to the receptor for the nominal and high cases is 0.68 mrem/yr. This dose, just as for the on-site area, results principally from dust inhalation and soil ingestion. In addition, as the distribution coefficient for Am-241 decreases, the significance of water-dependent pathways increases. At a distribution coefficient of 20 cm³/g (low case), the dose from Am-241 is 2.8 mrem/yr (310% increase). The worst case scenario predicts a dose of 43 mrem/yr (6200% increase), which is also less than the 100 mrem/yr standard in DOE Order 5400.5. Thus, ALARA considerations notwithstanding, the northern off-site area is not required to be remediated under DOE Order 5400.5. For the site to be released to the public, several other regulations, principally those under CERCLA, must be satisfied.

7.3.3 Southern Off-Site Contaminated Area

The maximum dose to the receptor considering for the nominal case is 2.7 mrem/yr. This dose is different from that for the on-site and northern contaminated areas (nominal cases) in that it results from Am-241 produced through water-dependent pathways. This results from the shallowness of the surficial material in the area. For the high case, the water-independent pathways are more significant. The maximum dose is 0.55 mrem/yr at time zero. For the low case, more Am-241 is leached into the groundwater. In addition, Pu-239 and Pu-240 are able to leach into the groundwater, albeit only slightly in 1,000 years. The maximum dose, from Am-241, is 44 mrem/yr. This is a 1500% increase over the dose for nominal K_d values. The worst case predicts a dose of 85 mrem/yr (3000% increase), which is also less than the 100 mrem/yr standard in DOE Order 5400.5. Thus, ALARA considerations notwithstanding, the southern off-site area is also not required to be remediated under DOE Order 5400.5. For the site to be released to the public, several other regulations, principally those under CERCLA, also must be satisfied.

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APPENDICES

APPENDIX A

A DESCRIPTION OF ROCKY FLATS AND HISTORY OF OPERABLE UNITS 2 AND 3

A.1 Description of Rocky Flats

RFP is located 16 miles northwest of Denver, Colorado, in Sects. 1 through 4 and 9 through 15 of Township 2 South, Range 70, west of the 6th Principal Meridian in northern Jefferson County. Nearby cities include Arvada, 5 miles southeast; Westminster, 7 miles east; Boulder, 12 miles north; and Golden and Lakewood, 15 miles south (DOE, 1992b).

The plant consists of approximately 6,550 acres of federally-owned and controlled property. Most of the major buildings are located on 400 acres of the Controlled Area (CA). The CA is surrounded by a 6,150 acre buffer zone. The northern boundary of the buffer zone lies on the county line between Jefferson and Boulder Counties and Colorado Highway 128. Jefferson County Highway 17 (Indiana Street) and State Highway 93 demarcate the eastern and western boundaries. Highway 72 and some agricultural and industrial properties lie on the southern boundary. Access to RFP is via Indiana Street or Colorado Highway 93 (DOE, 1992b).

RFP consists of approximately 180 permanent buildings, 60 trailers, and 50 ancillary support facilities. The trailers are used for temporary office space, and the support facilities consist of such structures as storage tanks, cooling towers, and electrical substations (EG&G, 1991a).

Of the 180 permanent buildings, only fifty-four (thirty percent) contain or have contained nuclear materials. Twenty-four of these are classified as production and process facilities, eight are storage buildings, and the remaining twenty-two are support buildings containing filter plenums or process waste pumping stations. Seventy-six (forty-two percent of the 180 permanent buildings are classified as non-nuclear facilities supporting both

nuclear and non-nuclear production operations. These buildings include chemical, gas, and metal storage shops, laboratories, fabrication, manufacturing, and plating facilities, and utility buildings such as pump houses, filter plenums, and emergency generator buildings. The remaining fifty buildings (twenty-eight percent) consist of office and administrative buildings, and support facilities such as guard posts, training facilities, library, and shower and locker facilities. Included in this number are the Rocky Flats water treatment plant, sewage treatment plant, steam plant, medical facility, and firehouse (EG&G, 1991a).

A.2 Detailed Description and History of the Contaminated Areas

A.2.1 Description and History of Operable Unit 2

OU 2 is located in the east and southeastern part of the main plant and buffer zone. It consists of three sites: the 903 Pad Area, the Mound Area, and the East Trenches Area. As shown in Fig. 3, the Mound Area is directly north and adjacent to the 903 Pad Area, and the East Trenches Area is immediately east of the Mound Area and northeast of the 903 Pad Area. OU 2 also includes an unused field adjacent to and directly east of the 903 Pad Area and directly south of the East Trenches Area. This field is bounded to the east and south by the buffer zone. The Mound Area, East Trenches Area, and the adjacent field have surface contamination of plutonium and americium deposited by wind from the 903 Pad Area. The following descriptions of the sites comprising OU 2 were taken from the *Final Phase II RFI/RI Work Plan (Alluvial)* except where noted.

A.2.1.1 903 Pad Area

The 903 Pad Area consists of five solid-waste management units (SWMUs): the 903 Pad (SWMU Ref. No. 112, also referred to as the 903 Drum Storage site); the 903 Lip site (SWMU Ref. No. 155); Trench T-2 site (SWMU Ref. No. 109); Reactive Metal Destruction site (SWMU Ref. No. 140); and the Gas Detoxification site (Ref. No. 183). The relative location of each site can be seen in Fig. 1.2.

Contamination of the 903 Pad area with plutonium and americium stemmed from the site's use for drum storage. This site was located under today's asphalt cap. The 903 Drum Storage area was used from October 1958 to January 1967 for storage of radioactively-contaminated oil drums (EG&G, 1991b).

Drums were stored in the open primarily in the northern and eastern portions of the area. Drums were not stored in the southwest portion, where Building 903 was constructed in 1967, and were only stored briefly in the southeast corner. During cleanup operations, some drums were stored just south of the fenced area (EG&G, 1992b).

Most of the drums transferred to the 903 Drum Storage area were nominal 50-gallon drums. However, a significant number of 30-gallon drums were also transferred. About three-quarters of the drums contained varying concentrations of plutonium, and most of the rest contained uranium. The drums principally contained spent lathe coolant, which consisted of a straight-chain hydrocarbon mineral oil and carbon tetrachloride in varying proportions. Other liquids present in drums were hydraulic oils, vacuum pump oils, trichloroethylene, perchloroethylene, silicon oils, acetone still bottoms, etc. The contents of the drums were originally marked on the outside, but because of weathering and poor record-keeping most of this information has been lost (EG&G, 1991b).

In 1964, drum leakage was noted during routine drum-handling operations. Figure 1.8, based on several aerial photographs taken from 1963 through 1969, shows the locations of Building 903, the barrel storage locations, and the areas of stained soil. Drum leakage was also noted in the 1950s; in 1959, or possibly earlier, attempts were made to minimize leakage by adding ethanolamine to the oil to reduce drum corrosion. Corrective actions initiated in 1965 consisted of transferring the contents of leaking drums to new drums, transferring the drums to Building 774, and fencing the area to restrict access

(EG&G, 1991b).

A total of 5,237 drums were stored at the 903 Drum Storage area before the material transfer to new drums began. The transfer reduced the number of drums to 4,826, and 3,572 of those drums contained plutonium-contaminated oil. These figures leave 411 drums unaccounted for, a discrepancy probably resulting from a combination of factors. First, not all of the original 5,237 drums were completely full. Second, all of the drums contained a layer of sludge at the bottom that took up some of the volume. This layer of sludge varied from 1/2 to 3 inches with an average depth of 1 inch. The sludge was estimated to contain 5,152 g (315.8 Ci) of plutonium by drum counter results. Oil Dry and MicroCel were added to absorb the sludge. The drums containing the plutonium sludge were encased in plastic, placed in boxes, and shipped for burial. Third, some of the oil was lost to leakage to the soil. Calculations (performed by Freiburg in 1970) indicated that an estimated 5,000 gallons of oil leaked from drums onto the ground at the Drum Storage Area. These calculations were based on the memory and knowledge of the personnel involved in site operations. The average plutonium concentration in the oil was 4.54×10^{-3} g per liter (280 pCi/l). Thus, an estimated 86 g (5.3 Ci) of plutonium were released into the soil at the 903 Drum Storage area (EG&G, 1991b).

In November 1968, site grading began at the 903 Drum Storage area in preparation for the addition of an asphalt cap over the contaminated area. This work also entailed moving contaminated soil from the outside of the fenced area to the inside; by May 1969, 33 drums of contaminated rocks had been moved from outside the fence. During the late summer of 1969, two courses of clean fill material were placed over the site. The asphalt cap was applied in October 1969, and an additional road base course was applied in February 1970 to contaminated soils directly east and south of the asphalt

was applied in February 1970 to contaminated soils directly east and south of the asphalt pad (EG&G, 1991b).

The asphalt containment pad is rectangular (about 395 ft by 370 ft). The pad dips slightly to the northeast at a drop of about 1 foot per 100 feet. The pad is 8 cm (3.2 in.) thick, and it is underlaid by approximately 15 cm (6 in.) of loose gravel and 8 cm of fill dirt (EG&G, 1991b).

During drum removal and cleanup of the 903 Drum Storage area, winds redistributed some of the contaminated soil to the south and east. An estimated 1 Ci (16.3 g) of plutonium was redistributed beyond the asphalt pad primarily to the south and the southeast. Of the estimated 1 Ci redistributed, approximately 0.56 Ci (9.1 g) is estimated to have been deposited upon the 903 Lip Site. The most contaminated area was adjacent to the pad to the south and southeast. A survey of the area indicated a maximum plutonium concentration of 2,258 pCi/g at the top 5 cm (2 in.) of soil (EG&G, 1991b).

Three separate soil cleanups were undertaken to remove plutonium-contaminated soil from three different areas within the 903 Lip Site. The first cleanup, from June through September 1976, consisted of hand-excavating contaminated soils from an area in the vicinity of the Reactive Metal Destruction Site until the soil contamination level was reduced below the detection limit of the Field Instrument for Detection of Low Energy Radiation (FIDLER), which is about 250 counts per minute (cpm). The excavated soil was loaded into 35 boxes, weighing a total of 125,000 pounds, which were shipped off-site for disposal (EG&G, 1991b).

The second soil cleanup, undertaken in June 1978, began north of the 1976 effort and utilized a front-end loader and bulldozer. All soil that exceeded 2,000 cpm in a

FIDLER survey was removed. Cleaned areas were resurveyed and soil removal continued until FIDLER readings were approximately 250 cpm. The contaminated soil was again loaded into boxes (1,448 boxes weighing approximately 4.7 million pounds) and shipped off-site for burial. Topsoil was applied over the excavated area, and the site was revegetated with native grasses (EG&G, 1991b).

As a result of the two soil-removal projects, approximately 0.5 Ci (8.2 g) of plutonium were removed from the 903 Lip Site. This estimate is based on an average soil plutonium concentration of 545 pCi/g of soil and a soil density of 1 g/cm³ (EG&G, 1991b).

The third soil-removal project was undertaken in 1984. It was performed along the eastern edge of the 903 Lip Site, and a total of 214 tri-walled pallets were filled with contaminated soil. The pallets were shipped off-site for disposal. The excavated area was covered with clean topsoil, as in the previous two projects (EG&G, 1991b).

The Trench T-2 site, located south of the 903 Pad and west of the Reactive Metal Destruction site, was used in 1968 for disposal of sanitary sewage sludge and flattened drums containing plutonium and uranium. The trench is believed to be about 15 ft x 200 ft x 5 ft. During the 1987 investigations, barrels were noted in the western end of Trench T-2 (EG&G, 1991b).

The Reactive Metal Destruction site is located on a hillside south of the 903 Drum Storage site. During the 1950s and 1960s, this site was used primarily for the destruction of lithium metal. Around 400 to 500 pounds of metallic lithium and smaller quantities of sodium, calcium, and magnesium, solvents, and unknown liquids were destroyed at this site. The residues, primarily nontoxic lithium carbonate, were also buried at this site (EG&G, 1991b).

The Gas Detoxification site located south of the 903 Pad consisted of Building

952, which was used between June 1982 and August 1983 to detoxify various bottled gases. Each bottle contained about 1 L of compressed gas consisting of various types of nitrogen oxides, chlorine, hydrogen sulfide, sulfur tetrafluoride, methane, hydrogen fluoride, and ammonia used in plant research and development. Various commercial neutralization processes were used to detoxify these gases. After neutralization, glassware used in the process was triple-rinsed, crushed, and disposed of in the present landfill. Neutralized gases released into the air during detoxification were no longer detectable (EG&G, 1991b).

A.2.1.2 Mound Area

The Mound Area is composed of four sites: Mound site (SWMU Ref. No. 113); Trench T-1 site (SWMU Ref. No. 108); Oil Burn Pit No. 2 site (SWMU Ref. No. 153); and Pallet Burn site (SWMU Ref. No. 154). The relative location of each site is indicated by Fig. 1.2.

The Mound site is located north of Central Avenue in the eastern Plant Security area. Between April 1954 and September 1958, the site was used to burn approximately 1,405 drums, primarily containing depleted uranium and beryllium-contaminated lathe coolant. Some drums contained enriched uranium- and plutonium-contaminated oil waste. The cleanup of the Mound site was completed in May 1970, and the contaminated materials were packaged and shipped to an off-site DOE facility for disposal (EG&G, 1991b).

Subsequent surficial soil sampling in the vicinity of the excavated Mound site indicated that the soil activity was between 0.8 and 112.5 dpm (0.4 to 51 pCi/g). This soil contamination is believed to have been transported from the 903 Pad Area by the wind because the plutonium contamination was limited to the surface (EG&G, 1991b).

The Trench T-1 site, located directly south of the Mound site, was used from 1954 until 1962 to dispose of approximately 125 drums filled with approximately 25,000 kg (55,115 lbs) of depleted uranium and plutonium chips coated with a small amount of lathe coolant. The estimated dimensions of the trench are 15 x 200 x 5 ft. It was covered with about two ft of soil, and the corners were marked (EG&G, 1991b).

Workers removing weeds in October and November 1968 unearthed two drums that were inadequately covered with fill material. The drums were sampled for plutonium and uranium content and taken off-site for disposal. One drum contained an oil-water mixture with 55 pCi/l of plutonium and 2.3×10^5 pCi/l of uranium, and the other contained an oily sludge with 4.6 pCi/g of plutonium and 1.2×10^6 pCi/g uranium (EG&G, 1991b).

Oil Burn Pit No. 2 is a site consisting of two parallel trenches used in 1957 and between 1961 to 1965 to burn approximately 1,082 drums of oil containing uranium. In April and May of 1957, the contents of an estimated 169 uranium-contaminated waste oil drums were burned. No further burning took place until 1961. From June 1961 to May 1965, the contents of approximately 914 drums were burned. Generally, the drums used for the oil-burning operations were reused, except for about 300 empty drums that were flattened and buried in the burning pits. The concentrations of uranium in the oil are not known. The residues from the oil-burning operations and the flattened oil drums were covered with backfill. In 1978, the soil around the oil burn pits was excavated to a depth of 5 ft, and 239 boxes (56 ft^3 per box) were filled with contaminated soil and shipped off site for disposal at an authorized DOE disposal site (EG&G, 1991b).

The Pallet Burn site located southwest of the Oil Burn Pit No. 2 site was reportedly used to burn wooden pallets in 1965. The types of hazardous or radioactive substances that may have been spilled on these pallets are unknown. This site was

cleaned up and reclaimed in the 1970s (EG&G, 1991b).

A.2.1.3 East Trenches Area

The East Trenches Area consists of nine burial trenches and two spray irrigation sites. These sites include: Trench T-3 (SWMU Ref. No. 110); Trench T-4 (SWMU Ref. No. 111.1); Trench T-5 (SWMU Ref. No. 111.2); Trench T-6 (SWMU Ref. No. 111.3); Trench T-7 (SWMU Ref. No. 111.4); Trench T-8 (SWMU Ref. No. 111.5); Trench T-9 (SWMU Ref. No. 111.6); T-10 (SWMU Ref. No. 111.7); Trench T-11 (SWMU Ref. 111.8); and the East Spray Irrigation sites (SWMU Ref. Nos. 216.2 and 216.3). Trenches T-3, T-4, T-10, and T-11 are located north of the east access road, and Trenches T-5 through T-9 are located south of the east access road. The spray irrigation areas are located east of Trenches T-5 through T-9. The relative locations of each site can be seen on Fig. 1.2.

Trenches such as Trench T-2 in the Mound Area were used from 1954 to 1965 for disposal of sanitary sludge. Approximately 125,000 kg of sanitary sludge contaminated with uranium and plutonium were buried, along with approximately 300 flattened empty drums contaminated with uranium. Contamination of the sludge ranged from 8.4×10^5 dpm/kg (382 pCi/g) to 7.9×10^6 dpm/kg (3,590 pCi/g). The activity in all the trenches in the East Trenches Area is estimated to total 100 to 150 millicuries. Trenches T-4 and T-11 also contain some plutonium and uranium-contaminated asphalt planking from the solar evaporation ponds. The wastes in these trenches have not been disturbed since their burial (EG&G, 1991b).

The East Spray Irrigation sites (SWMUs Ref. Nos. 216.2 and 216.3) were used for spray irrigation of sewage treatment plant effluent. In February and March 1989, effluent containing low concentrations of chromium was inadvertently sprayed in the area. The

chromium entered the sanitary sewage treatment plant after a spill in Building 444 (EG&G, 1991b).

A.2.2 Operable Unit 3 Description and History

OU 3 is unique among the operable units at RFP in that it is located outside of the plant boundaries. It consists of four IHSSs. IHSS 199 consists of all soils outside of the RFP boundary that are contaminated by releases from the plant. Therefore, the IHSS 199 boundary is delineated by the extent of off-site contamination, which has not been conclusively defined. IHSSs 200, 201, and 202 consist of three major water bodies nearby: the Great Western Reservoir, Standley Lake, and Mower Reservoir. Figure 1.2 shows the relative locations of these four sites in OU 3. The descriptions of IHSS 199 are taken from the *Final Past Remedy Report* and the descriptions of IHSS 200 - 202 are taken from the *Final Historical Information Summary and Preliminary Health Risk Assessment (Operable Unit 3 - IHSS 200-202)* except where noted.

A.2.2.1 IHSS 199: Off-Site Soil Contamination

Activities in IHSS 199 are principally concerned with approximately 350 acres of land, which was the subject of a 1975 lawsuit filed in U.S. District Court (Civil Action No. 75-M-1162) by the landowners, Church (McKay) and the Great Western Venture partnership, against Rockwell International Corporation, Dow Chemical Company, and the United States of America. The plaintiffs' holding consisted of about 2,000 acres of land to the west, south, and east of the plant. In the suit, the plaintiffs alleged that their lands were damaged by releases of plutonium and other radionuclides from RFP. They also alleged that these radioactive materials had rendered their property unfit for human habitation and had diminished its market value. Furthermore, the plaintiffs alleged that the mere presence of RFP next to their property further diminished the market value. In

turn, the defendants acknowledged that releases of radioactive materials occurred at various periods during the 1950s and 1960s, but they contended that these releases had not violated any applicable regulations (DOE, 1991a).

Both parties agreed to conduct a field investigation on the plaintiffs' land to assess the extent of contamination from plutonium and americium. The specific sampling methodology was agreed to by both parties before the commencement of the field investigation. The investigation was performed from 1977 to 1979, and it indicated that the plutonium concentration ranged from less than 0.01 to 3.4 pCi/g of soil [3.7×10^{-4} to 0.13 Becquerel per gram (Bq/g) of soil (DOE, 1991a)].

The Ackard-Butler interests intervened in March 1978 and were added to the lawsuit as plaintiffs. In 1982, the state of Colorado and Jefferson County, Colorado, were added to the lawsuit by amended complaint. The plaintiffs claimed that if the defendants prevailed in this litigation, then the state and county had acted unlawfully in precluding development of the plaintiffs' land. In the same year, the Court dismissed the plaintiffs' claims for lack of jurisdiction. The court ruled that the issues were not determinable under Rule 56. The next year, the Tenth Circuit Court of Appeals overturned the ruling and ruled that the plaintiffs were entitled to a trial or trials on some of their claims (DOE, 1991a).

In December 1984, the plaintiffs and defendants reached a settlement (U.S. District Court, 1985a). The settlement, as amended on July 2, 1985, required that RFP remediate the affected soils by ripping, plowing, and discing (commonly referred to as "tilling") of affected soils to reduce the concentration of plutonium to below the Colorado Department of Health special requirement standard of 0.9 pCi/g (0.03 Bq/g). Historical incidences, including the remediation of a B-52 crash site in Palomares, Spain, around

1960, set a precedent for tilling plutonium-contaminated lands. The tilling reduces the concentration of plutonium by uniformly dispersing it throughout the soil (Lawton, 1990). The option of remediating the required contaminated areas using other technologies was left open in the settlement. The settlement agreement also made provisions for future releases from RFP. If a release should occur, the plant must demonstrate that contaminants on any of the effected lands did not exceed applicable standards (DOE, 1991a).

Court-supervised soil sampling was conducted in 1985 on the effected lands, according to Colorado Department of Health sample collection protocol. The soil sampling indicated that approximately 350 acres (142 hectares) of land had plutonium concentrations greater than 0.9 pCi/g (0.03 Bq/g). These 350 acres were subsequently transferred to Jefferson County and the city of Broomfield and are the only lands in the suit to which the Court-ordered remediation action applies (DOE, 1991a).

The 1985 sampling data indicated that the average plutonium concentrations in the surficial soils appeared to have decreased significantly since the 1977 soil sampling, possibly because of migration. The decrease in average concentrations may have also been the result of the use of different laboratories using different analytical techniques, the significantly larger area represented by the 1985 samples [10 ac (4 ha)] per sample] as compared to the 1977 samples [0.2 ac (0.08 ha) per sample]), or the use of different soil sampling techniques used during the two studies (DOE, 1991a).

On May 28, 1986, Jefferson County requested that RFP remediate its lands. The city of Broomfield has not requested that the plant undertake remediation. Remedial actions have been implemented on two plots of land, a 20-acre plot in Sect. 18, T2S, R69W (the southern area) and a 100-acre plot in Sect. 7, T2S, R69W (the northern area).

These plots were tilled in strips as an erosion control measure (DOE, 1991a).

A.2.2.2 IHSS 200: Great Western Reservoir

IHSS 200 consists of Great Western Reservoir, off-site reaches of Walnut Creek, and downstream surface water possibly affected by outflow from the reservoir. The parts of Walnut Creek that flow inside the plant boundaries have been designated as OU 6.

The Great Western Reservoir, owned by the city of Broomfield, is located approximately 1.5 miles (2.4 km) east of RFP's western boundary in Sects. 6 and 7 of Township 2 South, Range 69 West (T2S, R69W). The reservoir is used solely as the municipal water supply for Broomfield, and the surrounding area is fenced and posted to prevent public access (DOE, 1991b).

"The original reservoir was built in 1904 as a irrigation water supply. The dam has been enlarged on several occasions, most recently in 1958. The maximum height of the dam is 69 feet (ft) (21 meters [m]). The present reservoir volume is 3,250 acre-feet (401 hectare-meters). The bottom and sides of the reservoir are unlined, meaning that the reservoir may be hydraulically connected to the groundwater system in the area" (DOE, 1991b)

Clear Creek, via Lower Church Ditch, is the primary source for the Great Western Reservoir. Until recently, the north and south branches of Walnut Creek, both of which flow from RFP, were also sources. In 1989 a chromic acid spill at RFP prompted the construction of a Walnut Creek diversion around the reservoir, known as the Broomfield Diversion Ditch. Flow from Walnut Creek is now treated and diverted south around the Great Western Reservoir and into the drainage below the reservoir outlet. There, it combines with the outflow from the reservoir. This ditch prevents surface water from Walnut Creek from reaching the reservoir. The outflow eventually discharges into Big Dry Creek several miles downstream from the reservoir (DOE, 1991b).

From 1952 through approximately 1979, water containing decontaminated process

and laundry effluent was discharged through the B-series ponds to South Walnut Creek. "Cooling tower blowdown and treatment system steam condensate were discharged to the A-series ponds, which feed into North Walnut Creek" (DOE, 1991b). Both of these discharges contained varying amounts of radionuclides that accumulated in the sediments of the holding ponds, Walnut Creek, and the Great Western Reservoir. "The EPA concluded in 1975 that historic releases of contaminants from the RFP to Great Western Reservoir resulted primarily from the following activities:

- early operational practices at the plant;
- reconstruction of the holding ponds between 1970 to 1973, which resuspended contaminated pond sediment and released some of it into the Great Western Reservoir;
- a 1973 release of tritium; and
- airborne transfer of plutonium" (DOE, 1991b).

In February and September of 1970, EPA conducted the first extensive sampling of bottom sediments in Great Western Reservoir. Results indicated a plutonium concentration above EPA's estimated baseline (worldwide atmospheric fallout) level of ≤ 0.1 pCi/g, or 0.0037 Bq/g (DOE, 1991b). "The thickness of the plutonium-bearing sediments was 2 inches (5 cm) or more at all sampling locations" (DOE, 1991b). The highest plutonium concentrations were detected in sediments in the Walnut Creek inlet area and the central section of the reservoir (leading to the dam inlet), and the lowest plutonium concentrations were found in the south arm, the shoreline area between the south arm and the dam, and the western portion of the north arm (DOE, 1991b).

In September of 1973, EPA resumed its investigation of plutonium in surface water sediments in the Great Western Reservoir, collecting sediment samples by both dredging and coring. The results of this second investigation indicated that plutonium

concentrations above the expected baseline concentrations were present throughout most of the entire bottom of the Great Western Reservoir. The maximum plutonium concentration detected was 4.5 pCi/g. The study also indicated that the areal distribution of plutonium delineated by the 1970 study was correct, but that the highest concentrations were found in the deepest areas of the reservoir rather than in the Walnut Creek inlet area. Finally, the study indicated that plutonium-239 concentrations in the uppermost sediment layer had increased substantially in the 3 years between the two studies. This increase was attributed to resuspension and transport of plutonium-239 from RFP holding ponds during reconstruction activities (DOE, 1991b).

In 1974, Battelle Pacific Northwest Laboratories conducted an investigation of radionuclide concentrations in reservoir and stream sediments near RFP. The study indicated that concentrations of plutonium-239, plutonium-240, and americium-241 in the sediments of Walnut Creek and the Great Western Reservoir exceeded EPA's baseline of ≤ 0.1 pCi/g (0.0037 Bq/g). The study also estimated that the total inventories of plutonium and americium in the sediment of Walnut Creek and the Great Western Reservoir were 73 mCi and 244 mCi (2.7 GBq and 9.02 GBq) respectively. Two separate periods of plutonium deposition were demonstrated from age-dated sediment cores (using cesium-137 as an age-dating marker) collected during the study. Both periods, 1968 to 1969 and 1959 to 1964, coincided with recorded, controlled, waterborne releases from RFP. Worldwide fallout from atmospheric nuclear weapons testing may have contributed to the plutonium deposition in the 1968 to 1969 sediment layer. In addition, the 1968 to 1969 peak detected in the Battelle study corresponded to a period of windborne releases from the 903 Pad (DOE, 1991b).

A second study was conducted in 1974 by Colorado State University on plutonium

in aquatic systems of RFP environs. The study indicated that the clay fraction of the sediments in the aquatic systems had an extremely high affinity for plutonium and, left undisturbed, provided an excellent retention mechanism for plutonium in the aquatic system. The study also indicated that plutonium absorption into the sediments was rapid and essentially irreversible (DOE, 1991b).

In 1975, Dow Chemical summarized the results of studies conducted through 1974. These studies indicated that plutonium in surface water impoundments was not readily transported from the impoundments, and that the majority of the plutonium released into surface waters was contained in the on-site holding ponds. The plutonium concentrations in Walnut Creek sediments increased downstream, suggesting the migration of plutonium released at an earlier time (DOE, 1991b).

Rockwell International performed several sediment measurements for plutonium and americium in 1979 and 1980 at the overflow spillway before the removal and disposal of the sediments by the city of Broomfield. Analysis of the sediment samples indicated that the concentration of plutonium-239, plutonium-240, and americium-241 were near the regional atmospheric fallout background concentrations and were well below the ≤ 0.9 pCi/g (0.03 Bq/g) Colorado Department of Health special construction requirements standard for plutonium in soil. Concentration varied little with respect to depth, supporting the conclusion that the sediments accumulated through a combination of hillslope erosion, wave action, and sediment mixing rather than the continuous lacustrine deposition typical of the reservoir bottom sediments (DOE, 1991b).

An extensive geochemical sampling project was conducted by Rockwell International in 1983. Forty-eight sediment grab samples and four sediment cores were collected along with some duplicate cores taken at three locations for joint analysis by the

city of Broomfield. Rockwell International recorded a maximum plutonium concentration of 5.4 pCi/g at a depth of 17 in. (43 cm), and the city of Broomfield recorded a maximum of 4.9 pCi/g at a depth of 7.5 in. (19 cm) (DOE, 1991b). "The study indicated that plutonium occurred in a discrete sediment horizon corresponding with historical releases from RFP, and that this horizon had been buried to varying depths by subsequent sedimentation. Sedimentation rates based on core samples were determined to vary from .14 in./yr (.35 cm/yr) in the eastern, deeper areas of the reservoir to <0.1 in./yr (<0.25 cm/yr) in the shallower areas. It was also concluded that no evidence existed of plutonium migration through the sediment column" (DOE, 1991b).

Numerous studies focusing on the soil surface contamination east of RFP have shown elevated concentrations of plutonium in soil to the north, west, and east of the Great Western Reservoir as a result of operations and cleanup at the 903 Drum Storage Area. The distribution of the plutonium contamination around the Great Western Reservoir indicates that windborne plutonium has contributed to the sediment contamination (DOE, 1991b).

A.2.2.4 IHSS 201: Standley Lake

IHSS 201 consists of Standley Lake, off-site reaches of Woman Creek (which flows into the reservoir from RFP), and downstream surface water features possibly affected by outflow from the reservoir. On-site portions of Woman Creek have been designated as OU 5. Standley Lake is a large reservoir used for municipal water supply and recreation. It is located 2 miles (3.2 km) southeast of RFP's eastern boundary (Fig. 2.1) in Sects. 16, 17, 20, 22, and 28, T2S R69W. The Farmer's Reservoir and Irrigation Company of Brighton, Colorado, has owned the reservoir since its construction between 1909 to 1919. The present volume of 43,000 acre-feet (5,300 hectare-meters) has remained relatively

unchanged since its construction, with the exception of periodic maintenance and reconstruction, most recently in 1978. Approximately two-thirds of the reservoir water is used as a municipal water supply for the cities of Westminster, Northglenn, and Thornton. The remaining one-third is transported through irrigation ditches to agricultural areas northeast of the lake, primarily between Broomfield and Fort Lipton. Clear Creek, via an irrigation ditch, is the source of approximately 96 percent of the water in Standley Lake. Woman Creek, which drains the southern side to RFP, also feeds the lake (DOE, 1991b).

Radioactive materials released from RFP may have been transported to Standley Lake through surface water (primarily in suspended sediments) and airborne particulates. From 1952 to 1973, RFP discharged water-treatment facility filter backwash into Pond C-1, which discharges into Woman Creek. Presently, only buffer zone surface runoff and natural groundwater seepage flow into the Woman Creek drainage within RFP boundaries (DOE, 1991b).

Many environmental studies have been conducted at the Great Western Reservoir and have included Standley Lake. In 1970, EPA collected four surface grab samples and two cores of bottom sediments from Standley Lake. The results indicated possible plutonium contamination above the estimated ≤ 0.1 pCi/g (0.0037 Bq/g) baseline concentration (worldwide atmospheric fallout) in the deeper areas of the reservoir. EPA concluded that the elevated plutonium concentrations in the sediments of Standley Lake resulted from unspecified releases from RFP. The agency also speculated that these plutonium releases occurred from surface water erosion and transport of plutonium-contaminated soil (DOE, 1991b).

In 1973, EPA resumed its investigation of plutonium in surface water sediments east of RFP. Seventeen surface grab samples and eight core samples were taken of

Standley Lake sediments. Analysis of the samples indicated that only two of the surface grab samples yielded plutonium concentrations above estimated baseline concentrations. Core samples taken at the same locations were similar to baseline concentrations (≤ 0.1 pCi/g). EPA determined that the cores were more representative of actual conditions and concluded that the sediment sampling program did not indicate any discernable plutonium contamination attributable to releases from RFP in the Standley Lake sediments (DOE, 1991b).

Battelle Pacific Northwest Laboratories conducted a sediment sampling investigation in 1974 in which eight surface sediment grab samples were collected and a single sediment core was taken from Standley Lake. Several of the samples contained plutonium concentrations that exceeded EPA's estimated baseline levels of ≤ 0.1 pCi/g (0.0037 Bq/g). The estimated total plutonium and americium inventories for Standley Lake sediments were 60 and 18 mCi (2.2 and 0.7 GBq/g), respectively, based on the single core sample. The core also indicated that the Cesium-137 concentration levels were typical of atmospheric fallout baseline levels (DOE, 1991b).

"Separate studies of plutonium in the surface water systems in the vicinity of RFP concluded that: (1) plutonium rapidly and almost irreversibly attaches itself to clay sediments (CSU, 1974), and; (2) plutonium in surface water impoundments does not move very far or very rapidly through subsurface waters, meaning that the majority of the plutonium released through RFP surface waters was contained in the on-site holding ponds" (DOE, 1991b).

Two sediment cores were collected by DOE in August of 1976. By correlating radionuclide concentrations, they determined that the longer core represented approximately 14 years, 1962–1976, of sedimentation.

"This dating enabled DOE to calculate an average sedimentation rate for the core location of 1.3 in/yr (3.4 cm/yr), and to conclude that plutonium concentrations in the core location exceeded baseline levels since 1966, peaked in 1969, and declined after 1969. The report attributed 70 percent of the plutonium in Standley Lake to releases from RFP and speculated that this plutonium was transported both by airborne particles and by soil erosion within the lake drainage basin (i.e., surface water). The time correlation of plutonium deposition in the core corresponded with the known period of windborne plutonium released from the 903 Pad at the RFP" (DOE, 1991b).

An extensive sediment sampling program was conducted by Rockwell International in 1984 to evaluate plutonium concentrations and to compare the results with previous sampling programs. Sixty-three surface sediment grab samples and four sediment cores were collected. The city of Westminster collected seven of the grab samples and two of the cores. The sampling indicated a maximum concentration of 0.61 pCi/g (0.02 Bq/g) at a depth of 6.3 to 7.1 in (16-18 cm). The maximum concentration detected in the surface grab samples was 0.55 pCi/g (0.018 Bq/g) (DOE, 1991b).

The CDH conducted a study to determine whether fish in Standley Lake were safe for human consumption. Selected metals, radionuclides, and priority organic pollutants were analyzed, and results showed no radionuclide contaminants in the fish tissues. Low concentrations of metals (cadmium, mercury, and selenium) and pesticides (DDT, DDE, DDD, and Malathion) were detected, none of which were unique to RFP operations (DOE, 1991b).

A.2.2.4 IHSS 202: Mower Reservoir

IHSS 202 consists of Mower Reservoir, off-site reaches of the irrigation ditch that feeds the reservoir from Woman Creek, and downstream surface water possibly affected by outflow from the reservoir. Areas of the irrigation ditch that lie on-site have been designated as OU 6.

Relatively little information is known about Mower Reservoir. It is a privately-

owned impoundment located just southeast of RFP in Sect. 18, T2S R69W, and is used strictly for agricultural purposes, primarily cattle watering and irrigation. Woman Creek, via Mower Ditch (an irrigation ditch that originates within RFP boundary), is its source. Mower Reservoir covers an area of approximately 9 acres (3.6 ha) and is roughly 50 ft (15 m) deep. It discharges to the southeast and eventually empties into Standley Lake. The reservoir is located on acreage that was the subject of the 1975 lawsuit (DOE, 1991b).

Only limited data have been collected to characterize Mower Reservoir. Because it is not a public water supply, the water quality is not monitored and has not been evaluated. Contamination emanating from RFP is proposed to have been transported primarily as airborne particulates, and to a lesser degree by surface water discharged into the Woman Creek drainage. It is inferred that the contribution of plutonium from surface water discharge via Woman Creek would be similar to that of IHSS 201, Standley Lake. It is also inferred that the plutonium contribution from airborne particulates and from erosion and transport of contaminated soils by surface runoff would be similar to that of IHSS 200, the Great Western Reservoir (DOE, 1991b).

In 1970, EPA, as a part of its study of plutonium contamination of the aquatic environs of RFP, performed the only sediment sampling of Mower Reservoir. A total of four surface sediment grab samples were taken. The analysis indicated that plutonium concentrations in the samples ranged from 0.09 to 0.18 pCi/g and averaged 0.14 pCi/g, which slightly exceeded EPA's estimated baseline concentration of ≤ 0.1 pCi/g. A number of nearby soil sampling tests have focused on elevated concentrations of plutonium, and it is expected that similar amounts of plutonium were deposited to both the nearby surficial soils and the Mower Reservoir (DOE, 1991b).

APPENDIX B

ENVIRONMENTAL AND EXPOSURE PATHWAY CHARACTERIZATION

The dose/soil concentration ratio is the product of the dose conversion factor (DCF), the environmental transport factor (ETF), and the source factor (SF). The DCF is a constant, and the SF is dependent only on the i th and j th radionuclide concentrations. Thus, the ETF is critical in determining the dose/soil concentration ratio for each pathway and radionuclide. Many of the computations made by RESRAD relate to the calculation of the ETFs.

This section presents the dose conversion factors used for the three exposure pathways and the equations used by RESRAD to calculate the ETF of each pathway and subpathway. All of the equations, except where noted, come from the RESRAD manual.

B.1 External Ground Radiation Exposure Pathway

External ground radiation exposure consists of only one pathway: ground radiation, which is illustrated in Fig. B.1.

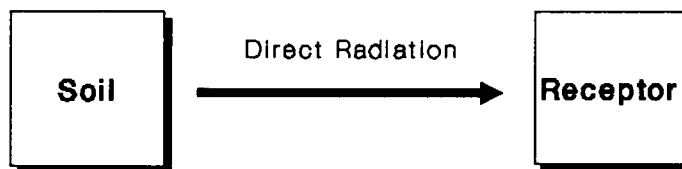


Figure B.1. External Ground Radiation Exposure Pathway.

Exposure to external radiation occurs primarily as a result of radiation emanating from radionuclides in a contaminated zone. Exposure can also occur from radiation emanating from radionuclides in the air, water, or ground surface that have been transported from their original location in the contaminated zone. In general, the

radiation dose resulting from these secondary sources is negligibly small compared with the dose resulting from direct exposure to the primary source (Yu, 1992). Therefore, RESRAD does not consider those secondary sources in the calculations.

"The contribution to the effective dose equivalent from the external ground radiation pathway for the i th principal radionuclide at time t following the radiological survey is given by the dose/source ratio $DSR_{i1}(t)$. This ratio may be expressed as a sum of products of dose conversion factors, environmental transport factors, and source factors " (Yu, 1992).

B.1.1 Dose Conversion Factors

"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 radionuclide present at 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 above the ground surface" (Yu, 1992). Table A.1 in the RESRAD manual lists DCFs for surface contamination (infinite thinness and lateral extent) and volume contamination (infinite depth and lateral extent). The values for plutonium and americium are provided in Table E.1. This assessment uses volume factors for $\rho_b = 1.6 \text{ g/cm}^3$ that are extrapolated from Table E.1.

B.1.2 Environmental Transport Factor

The 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 located at

distance C_d below the ground surface (Yu, 1992).

The ETF for the external ground radiation pathway is expressed in the following equation,

$$ETF_{i1}(t) = \rho_b^{(cz)} \times FO_1 \times FS_1 \times FA_1 \times FD_{i1}(t) \times FC_{i1}(t) \quad (B.1.)$$

where,

$\rho_b^{(cz)} =$	bulk density of soil material in the contaminated zone,
$FO_1 =$	occupancy and shielding factor (dimensionless),
$FS_1 =$	shape factor (dimensionless),
$FA_1 =$	area factor (dimensionless),
$FD_{i1}[\rho_b^{(cz)}, T(t)] =$	depth factor for radionuclide i at time t (dimensionless),
$FC_{i1}[\rho_b^{(cv)}, C_d(t)] =$	cover factor for radionuclide i at time t (dimensionless),
$T(t) =$	thickness of contaminated zone at time t (m)
$\rho_b^{(cv)} =$	bulk density of cover material, and
$C_d(t) =$	thickness of cover at time t (m) (Yu, 1992).

The bulk density of soil material in the contaminated zone, the occupancy and shielding factor, the shape factor, and the area factor are all input parameters described in Chapter 6. The depth factor FD_{i1} for a specified contaminated-zone thickness can be determined by interpolation or extrapolation from Table E.3 or approximated from equations A.2 and A.3 in the RESRAD Manual. The depth factor is a function of the bulk soil density and the contaminated zone thickness (which is time dependent).

The time dependence of the contaminated zone thickness is given by Eq. A.4 in the RESRAD manual. Since there is no cover material for any of the contaminated zone areas, Eqn. A.4 simplifies to the following equation,

$$T(t) = T(0) - v^{(cz)}(t) \quad 0 \leq t \quad (\text{B.2})$$

where,

$T(t)$ = thickness of the contaminated zone at time t (m),

$T(0)$ = initial thickness of the contaminated zone (m),

$v^{(cz)}$ = erosion rate of contaminated zone (m/yr).

Since none of the contaminated areas has any cover material, the cover factor, FC_{il} , for all radionuclides is equal to 1.0.

B.2 Inhalation Exposure Pathway

Inhalation exposure occurs from breathing in suspended contaminated dust particles, radon decay products, and other gaseous airborne radionuclides. These three inhalation pathways are illustrated in Fig. B.2.

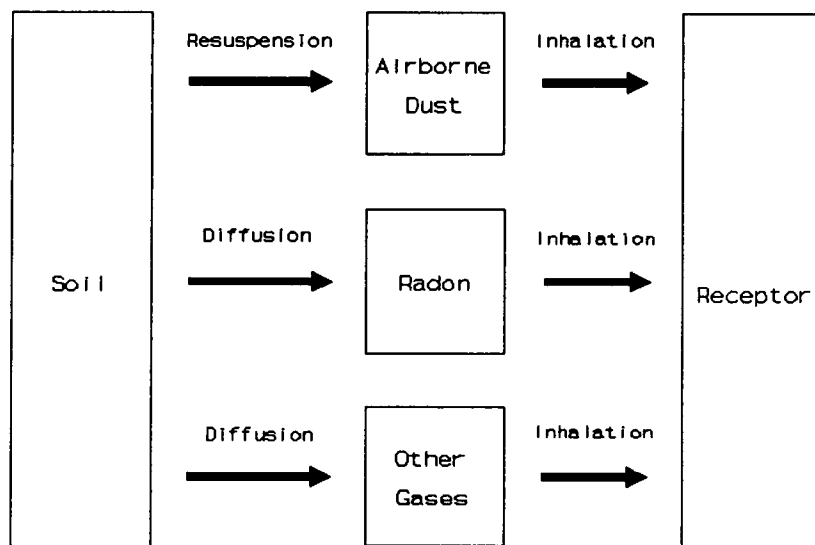


Figure B.2. Inhalation Exposure Pathways.

Only the dust environmental pathway is discussed in the conceptual model. "The

other gaseous airborne decay products are primarily tritium (in tritiated water vapor) and C-14 (in CO₂)" (Yu, 1992). They are not evaluated in the current version of RESRAD because their dose contribution in vapor form is insignificant to that relative to their liquid or solid form. Plutonium-239 and -242 eventually decay into radon products. However, the dose from radon products generated from the plutonium contamination is small because of the long half-lives of uranium isotopes. For this reason the radon environmental pathway was neglected in the conceptual model.

B.2.1 Dust Inhalation Pathway

Dust inhalation exposure results from breathing in resuspended dust particles contaminated with radionuclides. Fig. B.3 illustrates this pathway.

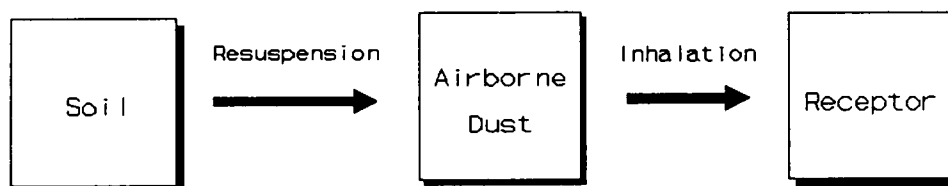


Figure B.3. Dust Inhalation Pathway.

"The contribution to the committed effective dose equivalent from the dust inhalation pathway for the i th principal radionuclide at time t following the radiological survey is given by the dose/source ratio $DSR_{i2}(t)$. This ratio may be expressed as a sum of products of dose conversion factors, environmental transport factors, and source factors " (Yu, 1992).

B.2.1.1 Dose Conversion Factors

"A dose conversion factor for inhalation is the dose/exposure ratio $DCF_{i2} = H_{E,i2}/E_{i2}$ for the committed effective dose equivalent $H_{E,i2}$ that is incurred by an individual from exposure by inhalation of a quantity E_{i2} of the i th principal radionuclide in

contaminated dust" (Yu, 1992). Table E.4 in Appendix E lists the dose conversion factors used by RESRAD. The values are for dust particles with an activity median aerodynamic diameter of 1 micron. The values for different inhalation classes are also listed. "The inhalation class for inhaled radioactive material is defined according to its rate of clearance from the lung. The three inhalation classes D, W, and Y correspond to retention half-times of less than 10 days, 10 to 100 days, and greater than 100 days, respectively" (Yu, 1992).

All isotopes of Plutonium are considered Class Y and Americium-241 is Class W.

B.2.1.2 Environmental Transport Factors

"An environmental transport factor for dust inhalation is the ratio $ETF_{i2}(t) = E_{i2}(t)/S_i(t)$ of the annual intake $E_{i2}(t)$ of the i th principal radionuclide by dust inhalation to the concentration $S_i(t)$ of that radionuclide in the soil for the i th year following the radiological survey" (Yu, 1992). It is expressed by the following equation,

$$ETF_{i2}(t) = ASR_2 \times FA_2 \times FCD_2(t) \times FO_2 \times FI_2 \quad (B.3)$$

where,

$ETF_{i2}(t)$ = environmental transport factor at time t for dust inhalation for the i th principal radionuclide (g/yr),

ASR_2 = air/soil concentration ratio, i.e., average mass loading of airborne contaminated soil particles (g/m^3),

FA_2 = area factor (dimensionless),

$FCD_2(t)$ = cover and depth factor (dimensionless),

FO_2 = occupancy factor (dimensionless), and

FI_2 = annual intake of air ($8,400 m^3/yr$)

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 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 exposed contaminated zone. The Gaussian plume model, as applied to annual average meteorological data, using sector averages, is generally regarded as applicable over distances from 100 meters to several thousand meters; it has not been validated for on-site exposure in which the exposure occurs immediately above the source. There are uncertainties regarding exposure in the immediate area, primarily because of possible air turbulence or downdrafts created by buildings and structures. Considering these uncertainties regarding the Gaussian plume model for on-site exposure and the large increase in the size of the code that incorporation of an area-source Gaussian plume model would entail, a simple mixing model has been used in the current version of RESRAD (Yu, 1992).

The area factor, FA_2 , is the fraction of airborne dust per unit area that is contaminated. A mixing model is used to calculate the area factor. This model estimates the dilution of contaminated dust that is resuspended on-site by uncontaminated dust blown in from off-site. The area factor is calculated by the following formula,

$$FA_2 = \frac{A^{\frac{1}{2}}}{A^{\frac{1}{2}} + DL} \quad (B.4)$$

where,

A = area of contaminated zone (m^2), and

DL = dilution length (m)

The air/soil concentration ratio, the occupancy factor, and the dilution length are input parameters and the annual intake of air is a constant. All of these parameters are discussed in Chapter 6.

The cover and depth factor, FCD_2 , represents the fraction of resuspendable soil particles at the ground surface that is contaminated. It is calculated by assuming that mixing of the soil will occur within a layer of thickness d_m at the surface. The cover and depth factor is given by Eq. B.5 in the RESRAD manual. Because there is no cover material for any of the contaminated zone areas, Eq. B.5 simplifies to the following equation,

$$FCD_2(t) = \begin{cases} 1 & T(t) \geq d_m \\ T(t)/d_m & T(t) < d_m \end{cases} \quad (B.5)$$

where,

d_m = depth of soil mixing layer (0.15 m),

$T(t)$ = thickness of contaminated zone at time t (m)

B.3 Ingestion Exposure Pathway

Ingestion exposure has 6 pathways: plant, meat, milk, fish, water, and soil.

Associated with these 6 ingestion pathways are 14 subpathways, illustrated in Fig. B.4.

The 14 subpathways can be divided into two basic categories: water-dependent and water-independent, as illustrated in Table B.1. Water-dependent pathways involve transport through groundwater or surface water and water-independent pathways do not.

The doses from these pathways are calculated from the sums of products of DCFs (that characterize the exposure pathways), ETFs (that characterize the environmental pathways), and SFs (that characterize ingrowth, decay, and leaching of the radionuclides).

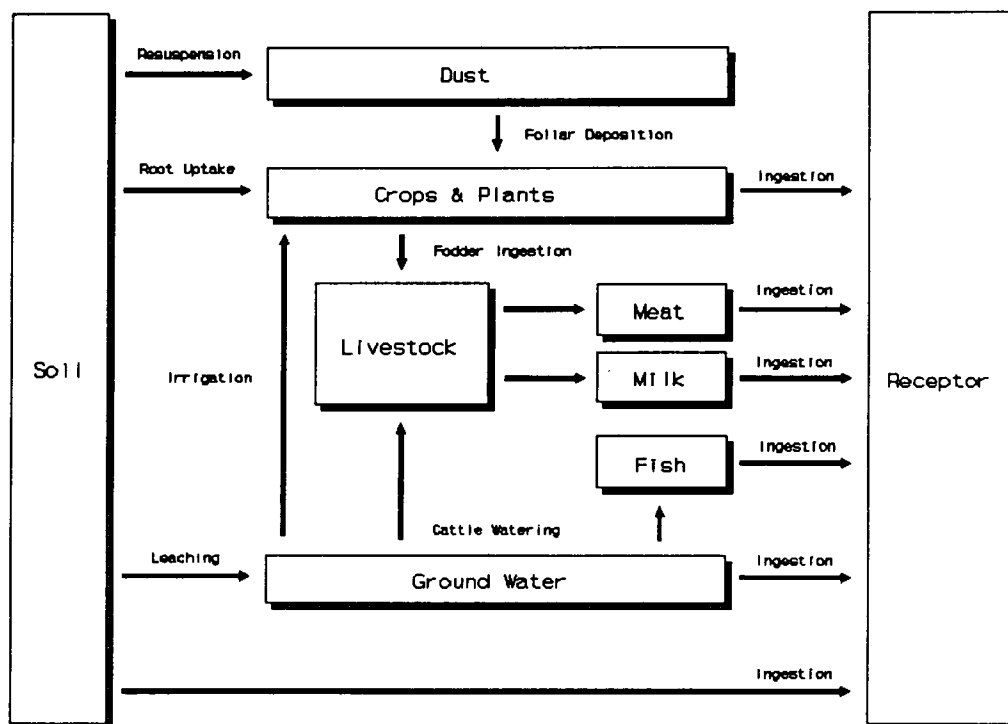


Figure B.4. Ingestion Exposure Pathway.

DCFs for ingestion are described in Section B.4.3.1.

B.3.1 Dose Conversion Factors

"A dose conversion factor for ingestion is the dose/exposure ratio $DCF_{i3} = H_{E,i3}/E_i$, where $H_{E,i3}$ is the committed effective dose equivalent incurred by an individual from intake by ingestion of a quantity E_i of the i th principal radionuclide" (Yu, 1992). Table 4.8 lists the dose conversion factors used in the calculations. "Dose conversion factors depend on the chemical form, which determines the fraction f_1 of a radionuclide entering the gastrointestinal (GI) tract that reaches body fluids. Data on the appropriate fractions for different chemical forms are given in Publication No. 30 of the International Commission on Radiological Protection" (Yu, 1992). The default DCFs are used and are

Table B.1. Environmental Transport Pathways for Ingestion

Environmental Pathways	Environmental Subpathways	Category
Soil		Water-Independent
Crops and Plants	Foliar Deposition	Water-Independent
	Root Uptake	Water-Independent
	Irrigation (Ditch)	Water-Dependent
Meat	Foliar Deposition ¹	Water-independent
	Root Uptake ¹	Water-independent
	Irrigation (Ditch) ¹	Water-dependent
	Cattle Watering	Water-dependent
Milk	Foliar Deposition ¹	Water-independent
	Crops and Plants ¹	Water-independent
	Irrigation (Ditch) ¹	Water-dependent
	Cattle Watering	Water-dependent
Drinking Water		Water-dependent
Fish		Water-dependent

¹ Subpathways derived from crops and plants used as animal fodder

the largest values of f_1 . Table E.5 in Appendix E lists the DCFs for all of the isotopes of Plutonium and Americium-241.

B.3.2 Environmental Transport Factors

B.3.2.1 Plant Ingestion Pathway

This ingestion pathway involves the consumption of contaminated crops and plants grown by the farmer/receptor in the contaminated zone areas. This ingestion pathway consists of four subpathways: root uptake, foliar deposition, ditch irrigation, and overhead irrigation. RESRAD considers only one of the two types of irrigation is being used. For this assessment ditch irrigation is assumed. Fig. B.5 illustrates the plant ingestion pathway.

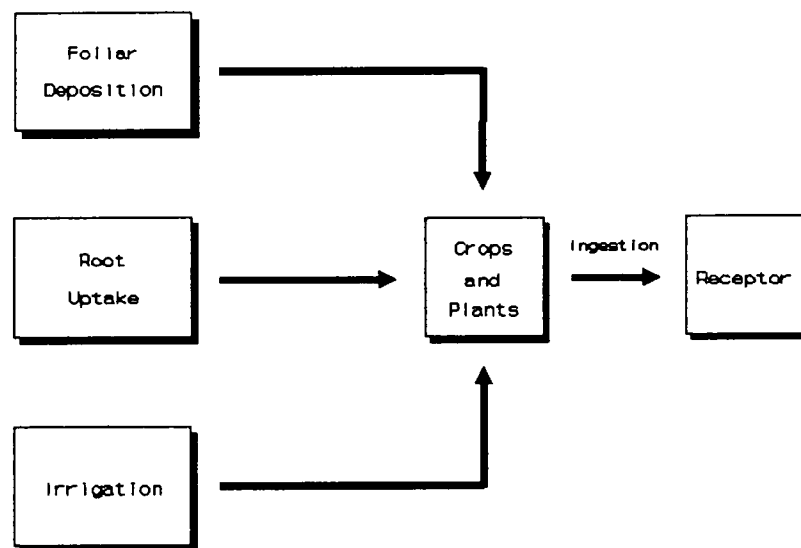


Figure B.5. Plant Ingestion Pathway.

The general ETF for the plant ingestion pathway is given by the following equation,

$$EFT_{i3q}(t) = FA_3 \times FCD_{3q}(t) \times \sum_k DF_{3k} \times FSR_{i3qk}(t) \quad (B.6)$$

where,

$ETF_{i3q}(t)$ = environmental transport factor for the i th principal radionuclide and pq th environmental pathway at time t (g/yr),

q = secondary index for root uptake ($q=1$), foliar deposition ($q=2$), ditch irrigation ($q=3$), overhead irrigation ($q=4$), and livestock water ($q=5$),

FA_3 = area factor for plant environmental transport pathway (dimensionless),

$FCD_{3q}(t)$ = cover and depth factor for the plant ingestion subpathways, q , at time t (dimensionless),

DF_{3k} = dietary factor = annual consumption of the k th food class for the p th food pathway (g/yr),

k = food class index, and

$FSR_{i3qk}(t)$ = food/soil concentration ratio for the i th principal radionuclide, pq th ingestion pathway, and k th food class at time t (dimensionless)

This general equation is also used for the meat and milk ingestion pathways. The specific ETFs for each of the three subpathways of the plant ingestion pathway are given in the respective sections.

Both the area factor and the dietary factor remain the same for all of the subpathways. The area factor for the plant (FA_3) environmental transport pathway is given by the following relationship,

$$FA_3 = \begin{matrix} A/2,000 & 0 \leq A \leq 1,000 \text{ m}^2 \\ 0.5 & A > 1,000 \text{ m}^2 \end{matrix} \quad (B.7)$$

where,

$A =$ area of contaminated zone (m^2).

The dietary factors consist of the average quantity of the respective food classes that are consumed annually by the target receptor. "The sum is over the applicable food classes. The plant pathway consists of two food classes: (1) fruit, nonleafy vegetables, and grain ($k=1$) and (2) leafy vegetables ($k=2$). For the meat and milk pathways, only a single food class is used in the current version of RESRAD" (Yu, 1992). For the all of the plant ingestion subpathways $DF_{31} = 160$ kg/yr ($k=1$) and $DF_{32} = 14$ kg/yr. Table E.6 lists the factors for all of the food classes.

The cover and depth factors, $FCD_{3q}(t)$, and the food/soil concentration ratios, $FSR_{i3qk}(t)$, for the four plant ingestion subpathways are presented separately in their respective sections.

The ETFs for the water-dependent environmental pathways listed in Table B-1 can be calculated by modifying the food/source concentration ratio in the above equation. Thus, the food/source ratio is the sum of the products,

$$FSR_{i3qk}(t) = FWR_{i3qk} \times WSR_{ir}(t) \quad (B.8)$$

where,

$FWR_{i3qk} =$ food/water concentration ratio for the i th principal radionuclide, plant water-dependent pathway, q th water-dependent subpathway, and k th food class (L/g),

$WSR_{ir}(t) =$ water/soil concentration ratio for the r th water pathway segment (g/L), and

$r =$ water pathway segment index for groundwater ($r=1$) or surface water ($r=2$)

By substituting Eq. B.8 into Eq. B.6, one obtains

$$ETF_{i3qr}(t) = WEF_{i3q}(t) \times WSR_{ir}(t) \quad (B.9)$$

where,

$$WEF_{i3q}(t) = FA_3 \times FCD_{3q}(t) \times \sum_k DF_{3k} \times FWR_{i3qk} \quad (B.10)$$

is the water exposure factor for the q th subpathway in units of L/yr, and the quantities on the right are as defined for Eqs. B.6 and B.8. "A water exposure factor is equal to the ratio of the annual intake of the i th principal radionuclide in food contaminated through the q th water-dependent subpathway to the concentration of the radionuclide in the contaminated water" (Yu, 1992). The above equation is also used for the meat ($p=4$) and the milk ($p=5$) ingestion pathway.

Individual plant environmental transport subpathways are explained in more detail in the following sections.

B.3.2.1.1 Root Uptake Environmental Transport Subpathway

The root uptake subpathway for the plant ingestion pathway involves radionuclide contaminants that are absorbed by plants and crops through their roots. This subpathway is illustrated in Fig. B.6.

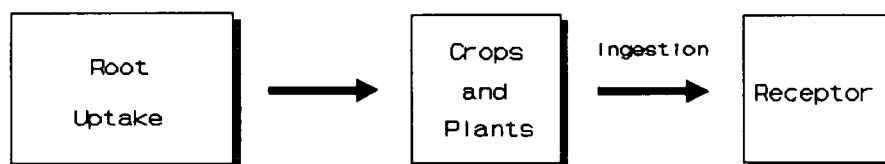


Figure B.6. Root Uptake Subpathway.

The ETF for the root uptake subpathway of the plant ingestion pathway is given by the following equation,

$$ETF_{i3l}(t) = FA_3 \times FCD_{i3l}(t) \times \sum_k^2 DF_{3k} \times FSR_{i3lk} \quad (B.11)$$

The area factor, FA_3 , and the dietary factors, $DF_{3(1,2)}$, are discussed in Sect. B.3.2.1. The cover and depth factor is given by the following formula,

$$FCD_{3l}(t) = \begin{cases} 1 & T(t) \geq d_r \\ T(t)/d_r & T(t) < d_r \end{cases} \quad (B.12)$$

where,

$T(t)$ = thickness of contaminated zone at time t (m), and

d_r = maximum root depth (0.9 m)

Eq. 4.32 "...is based on the assumption of a sharp boundary between the bottom of any uncontaminated cover and the top of the contaminated zone. The effect of mixing uncontaminated and contaminated soil in a surface layer by plowing or other disturbance of soil close to the ground surface is not taken into account" (Yu, 1992).

The plant food/soil concentration ratios for root uptake are given by the following relationship,

$$FSR_{i3lk} = B_{iv} \quad (B.13)$$

The coefficient, B_{iv} , is the vegetable/soil transfer factor for radionuclide i . "It is assumed that the same root uptake transfer factor can be used for nonleafy vegetables ($k=1$) and leafy vegetables ($k=2$)" (Yu, 1992). The values for B_{iv} are presented in Table E.7.

B.3.2.1.2 Foliar Deposition Subpathway

The foliar deposition subpathway for the plant ingestion pathway results from contaminated dust deposited on the foliage and absorbed. Fig. B.7 illustrates this

subpathway.

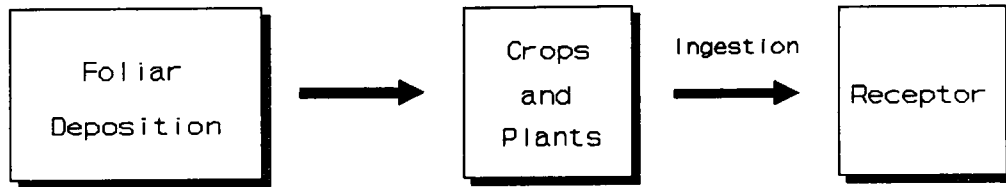


Figure B.7. Foliar Deposition Subpathway.

The ETF for the foliar deposition subpathway of the plant ingestion pathway is given by the following equation,

$$ETF_{i32}(t) = FA_3 \times FCD_{i32}(t) \times \sum_k^2 DF_{3k} \times FSR_{i32k} \quad (B.14)$$

The area factor, FA_3 , and the dietary factors, $DF_{3(1,2)}$, are the same as for the root uptake subpathway as explained in Sect. 4.5.3.2.1. "The cover and depth factor $FCD_{p2}(t)$ for foliar deposition of the ingestion pathway is the same as the cover and depth factor $FCD2(t)$ for the inhalation pathway" (Yu, 1992). As described in Section 4.5.2.1.2.2, the cover and depth factor is given by the following relationship,

$$\begin{aligned} FCD_{32}(t) &= FCD_2(t) = 1 & T(t) &\geq d_m \\ &= T(t)/d_m & T(t) &< d_m \end{aligned} \quad (B.15)$$

where,

d_m = depth of soil mixing layer (0.15 m)

$T(t)$ = thickness of contaminated zone at time t (m),

The plant-food/soil concentration ratio for uptake from airborne contaminants deposited on foliage is given by the following relationship,

$$FSR_{i32k} = FA_2 \times FAR_{i32k} \times ASR_3 \quad (B.16)$$

where,

FSR_{i32k} = plant-food/soil concentration ratio for foliar deposition for the i th principal radionuclide and k th food class (dimensionless),

FA_2 = area factor for dilution of resuspended contaminated dust (dimensionless),

FAR_{i32k} = plant-food/air concentration ratio for radionuclide transfer by airborne foliar deposition for the i th principal radionuclide and k th food class (m^3/g), and

ASR_3 = air/soil concentration ratio, specified as the average mass loading of airborne contaminated soil particles in a garden during the growing season ($1 \times 10^{-4} g/m^3$ default)

The area factor for dilution of resuspended contaminated dust by mixing with uncontaminated dust blown in from off-site is given by Eq. B.4. The plant-food/air concentration ratio is given by the following equation,

$$FAR_{i32k} = \frac{3.16 \times 10^4 \times [(V_{di} \times f_r \times T_{ivk})(1 - \exp(-\lambda_w t_{ek}))]}{Y_{vk} \times \lambda_w} \quad (B.17)$$

where,

V_{di} = deposition velocity of contaminated dust ($1 \times 10^{-3} m/s$ for Pu and Am),

f_r = fraction of deposited radionuclides retained on the vegetation (0.25, dimensionless),

T_{ivk} = foliage-to-food radionuclide transfer coefficient for the i th principal radionuclide and k th food class ($T_{iv1} = 0.1$, $T_{iv2} = 1.0$, and $T_{iv3} = 1.0$, dimensionless)

Y_{vk} = wet-weight crop yield for the k th food class ($Y_{v1} = 0.7 kg/m^2$, $Y_{v2} = 1.5 kg/m^2$, and $Y_{v3} = 1.1 kg/m^2$),

λ_w = weathering removal constant for vegetation ($20 yr^{-1}$), and

t_{ek} = time of exposure of the k th food class to contamination during the growing season ($t_{e1} = 0.17 yr$, $t_{e2} = 0.25 yr$, and $t_{e3} = 0.08 yr$) (Yu, 1992).

"The numerical factor $3.16 \times 10^4 (kg/g)(s/yr)$ is used to convert FAR_{i32k} to units of

m^3/g . The foliage-to-food transfer coefficient T_{fvk} is assumed to be radioactive independent in the current version of the code. The weathering removal constant corresponds to a contaminant removal half-time of two weeks" (Yu, 1992). The values for $k=3$ are for fodder and are not included in the sum over k in Eq. B.17.

B.3.2.1.3 Ditch Irrigation Subpathway

The ditch irrigation subpathway involves radionuclides deposited on crops and plants from contaminated groundwater used for irrigation. Fig. B.8 illustrates this subpathway.

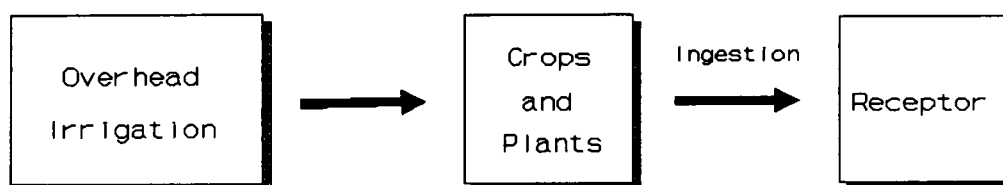


Figure B.8. Ditch Irrigation Subpathway.

The ETF for this subpathway is given by the following equation,

$$ETF_{i33}(t) = FA_3 \times FCD_{33}(t) \times \sum_k^2 DF_{3k} \times FSR_{i33k} \quad (\text{B.18})$$

where,

$ETF_{i33}(t)$ = environmental transport factor for the i th principal radionuclide and the ditch irrigation subpathway ($q=3$) of the plant ingestion pathway ($p=3$) (g/yr),

FA_3 = area factor for plant environmental transport pathway (dimensionless),

$FCD_{33}(t)$ = cover and depth factor for the ditch irrigation subpathway ($q=3$) of the plant ingestion pathway ($p=3$) at time t (dimensionless),

DF_{3k} = dietary factor = annual consumption of the k th food class (g/yr),

k = food class index, and

$FSR_{i33k}(t)$ = food/soil concentration ratio for the i th principal radionuclide, ditch irrigation subpathway ($q=3$) of the plant ingestion pathway ($p=3$), and k th food class at time t (dimensionless) (Yu, 1992).

The area and dietary factor are the same as in the two proceeding subpathways.

"The contributions from ditch irrigation ($q=3$), overhead irrigation ($q=4$), and livestock water ($q=5$) are independent of the depth of the contaminated zone in the models used because the infiltrating water will carry the contamination to the aquifer and contaminate the water regardless of the depth, and the subsequent contamination mechanisms do not depend on depth" (Yu, 1992). The cover and depth factors for these subpathways are,

$$FCD_{p3}(t) = FCD_{p4}(t) = fcd_{p5}(t) = 1 \quad (B.19)$$

The plant-food/soil concentration ratio for ditch irrigation is given by,

$$FSR_{i33k}(t) = FWR_{i33k} \times [WSR_{i1}(t) \times FI_1 + WSR_{i2}(t) \times (F - FI_1)] \quad (B.20)$$

where,

$FSR_{i33k}(t)$ = plant-food/soil concentration ratio for ditch irrigation for the i th principal radionuclide and k th food class at time t (dimensionless),

FWR_{i33k} = plant-food/water concentration ratio for ditch irrigation for the i th principal radionuclide and the k th food class (L/g),

$WSR_{i1}(t)$ = well-water/soil concentration ratio for the i th principal radionuclide (g/L),

FI_1 = fraction of well water used for irrigation (balanced from surface water; 1.0, dimensionless), and

$WSR_{i2}(t)$ = surface-water/soil concentration ratio for the i th principal radionuclide (g/L) (Yu, 1992).

The equation for the plant-food/water concentration ratio, FWR_{i33k} , for ditch irrigation is,

$$FWR_{i33k} = \frac{[I_{rr} \times B_{iv} \times (1 - \exp(-L_i t_{ek}))]}{[Y_{vk} \times L_i]} \quad (B.21)$$

where,

I_{rr} = irrigation rate (0 m/yr), and

L_i = leach rate constant for radionuclides i (yr^{-1}),

FWR_{i33k} is in dimensions of L/g (m^3/kg), B_{iv} is as defined for Eq. B.13, and t_{ek} and Y_{vk} are as defined for Eq. B.17. The leach rate constant L_i is discussed in Appendix E. The default value used in the RESRAD code for fraction of well water used for irrigation is 1.0, i.e., 100 percent of irrigation water is well water. A value of 0.5 means 50 percent of irrigation water is well water and 50 percent is surface (pond) water. The water/soil concentration ratios are discussed in Appendix D.

B.3.2.2 Meat and Milk Ingestion Pathway

The meat and milk ingestion pathways result from the ingestion of meat and milk from livestock that have ingested contaminated fodder. These two ingestion pathways are illustrated in Fig. B.9.

The ETFs for the meat and milk ingestion pathways are given by the following equation,

$$ETF_{i(4,5)q}(t) = FA_{(4,5)} \times FCD_{(4,5)q}(t) \times DF_{(4,5)} \times FSR_{i(4,5)qk}(t) \quad (B.22)$$

where,

$ETF_{i(4,5)q}(t)$ = environmental transport factor for the i th principal radionuclide, meat ($p=4$) and milk ($p=5$) pathway, q th subpathway at time t (g/yr),

q = secondary index for root uptake ($q=1$), foliar deposition ($q=2$), ditch irrigation ($q=3$), overhead irrigation ($q=4$), and livestock

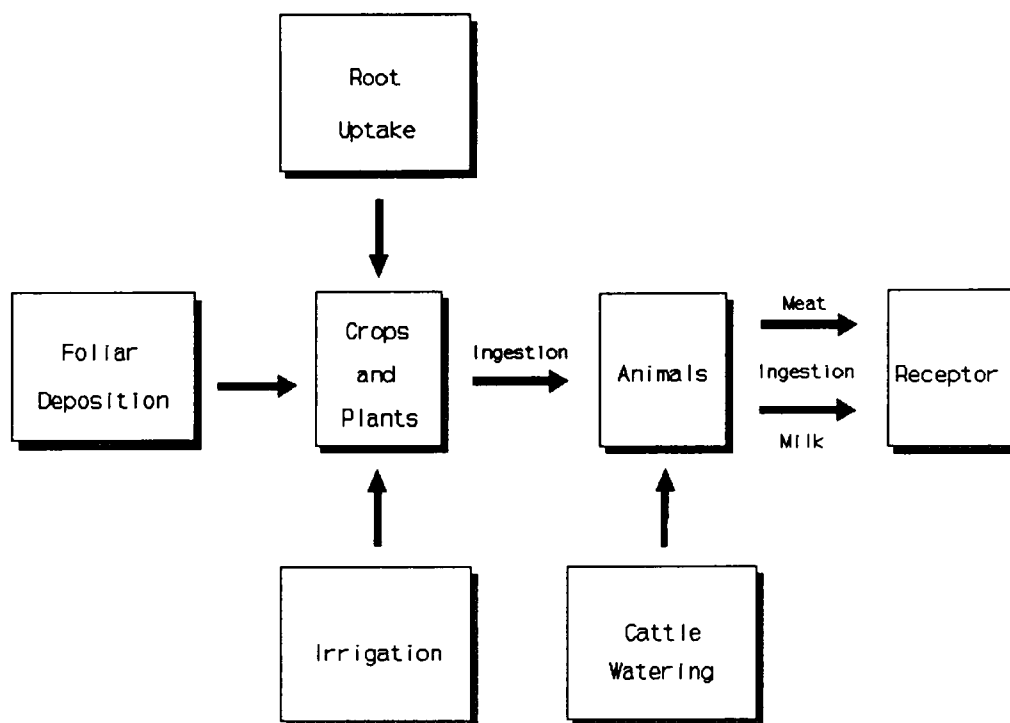


Figure B.9. Meat and Milk Ingestion Pathways

water ($q=5$),

$FA_{(4,5)} =$ area factor for meat and milk environmental transport pathway (dimensionless),

$FCD_{(4,5)q}(t) =$ cover and depth factor for the meat ($p=4$) and milk ($p=5$) ingestion pathway, qth subpathway at time t (dimensionless),

$DF_{(4,5)} =$ dietary factor = annual consumption of meat (kg/yr) and milk (L/yr) and,

$FSR_{i3qk}(t) =$ food/soil concentration ratio for the i th principal radionuclide, meat ($p=4$) and milk ($p=5$) pathway, and qth subpathway at time t (dimensionless)

"For the meat and milk pathways, only a single food class is used in the current version of RESRAD" (Yu, 1992).

The area factor for the meat (FA_4) and milk (FA_5) pathways is given by

$$\begin{aligned} FA_4 = FA_5 &= A/20,000 & 0 \leq A \leq 20,000 \text{ m}^2 \\ &= 1 & A > 20,000 \text{ m}^2 \end{aligned} \quad (\text{B.23})$$

where,

A = area of contaminated zone (m^2).

This relationship is true for all of the meat and milk environmental transport subpathways.

The cover and depth factor for root uptake ($q=1$) for the meat and milk pathway is,

$$\begin{aligned} FCD_{(4,5)}(t) &= 1, & T(t) \geq d_r \\ &= T(t)/d_r, & T(t) < d_r \end{aligned} \quad (\text{B.24})$$

$T(t)$ = thickness of contaminated zone at time t (m), and

d_r = maximum root depth (0.9 m)

The dietary factors, $DF_{(4,5)}$, for meat ($p=4$) and milk ($p=5$) are presented in Table 4.11. These factors are,

$$\begin{aligned} DF_4 &= 63 \text{ kg/yr} & (\text{meat}) \\ DF_5 &= 92 \text{ L/yr} & (\text{milk}) \end{aligned}$$

The food/soil concentration ratios $FSR_{ipq}(t)$ for meat and milk can be factored into the product,

$$FSR_{ipq}(t) = FQR_{ip} \times FI_{pq} \times QSR_{ipq}(t) \quad (\text{B.25})$$

where,

FQR_{ip} = radionuclide transfer factor for meat ($p=4$) or milk ($p=5$) = ratio of the concentration of the i th principal radionuclide in meat or milk in pCi/kg to the rate of intake in fodder or water by livestock of the i th principal radionuclide in pCi/d (d/kg),

FI_{pq} = daily intake of fodder ($q=1,2,3$, and 4) or water ($q=5$) by livestock (kg/d-see below for default values), and

$QSR_{ipq}(t)$ = fodder/soil or livestock-water/soil concentration ratio for meat ($p=4$) or milk ($p=5$) for the i th principal radionuclide and q th subpathway (dimensionless).

The radionuclide transfer factors FQR_{ip} are listed in Table E.8 in Appendix E. The livestock fodder intake rates are $FI_{4q} = 68 \text{ kg/d}$ and $FI_{5q} = 55 \text{ kg/d}$ for $q=1, 2, 3$, and 4 for meat and milk, respectively, and the livestock water intake rates are $FI_{45} = 50 \text{ L/d}$ and $FI_{55} = 160 \text{ L/d}$ for $q=5$. (Note that 1 L of water weighs 1 kg; hence, units of kg/d may be used for all intakes.)

B.3.2.2.1 Root Uptake Subpathway

The root uptake subpathway for the meat and milk ingestion pathways involves plants and crops that absorb radionuclide contaminants through their roots and are subsequently consumed by livestock. This subpathway is illustrated in Fig. B.10.

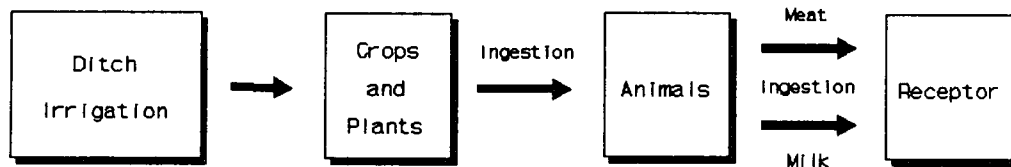


Figure B.10. Root Uptake Subpathway.

The ETF for the root uptake subpathway of the meat and milk ingestion pathway is given by the following equation,

$$ETF_{i(4,5)t}(t) = FA_{(4,5)} \times FCD_{i(4,5)1}(t) \times DF_{(4,5)} \times FSR_{i(4,5)1} \quad (B.26)$$

The area factor, the cover and depth factor, and the dietary factor are the same for all of the meat (FA_4) and milk (FA_5) subpathways. The area factor is given by equation B.23. The dietary factors are given in Table 4.9. The cover and depth factor for root uptake is given by the following equation:

$$FCD_{p1}(t) = \begin{cases} 1, & T(t) \geq d_r \\ T(t)/d_r, & T(t) < d_r \end{cases} \quad (B.27)$$

The food/source concentration ratios for the meat and milk ingestion, root uptake subpathway, $FSR_{i(4,5)1}$, are given by the following equation,

$$FSR_{i(4,5)1} = FQR_{i(4,5)} \times FI_{i(4,5)1} \times QSR_{i(4,5)1}(t) \quad (B.28)$$

FQR_{i4} and FQR_{i5} are both given by Table D.4 in the RESRAD manual.

$FI_{41} = 68 \text{ kg/d}$ and $FI_{51} = 55 \text{ kg/d}$ (default values).

The formulas for the fodder/soil concentration ratios for root uptake are as follows,

$$QSR_{i41} = QSR_{i51} = B_{iv} \quad (B.29)$$

is the ratio for root uptake by fodder, where B_{iv} is the vegetable/soil transfer factor for root uptake, tabulated in Table D.3 in the RESRAD manual.

B.3.2.2.2 Foliar Deposition Subpathway

The foliar deposition subpathway for the meat and milk ingestion pathway results from contaminated dust that is deposited on the foliage and absorbed. The foliage is subsequently consumed by livestock. Fig. B.11 illustrates this subpathway.

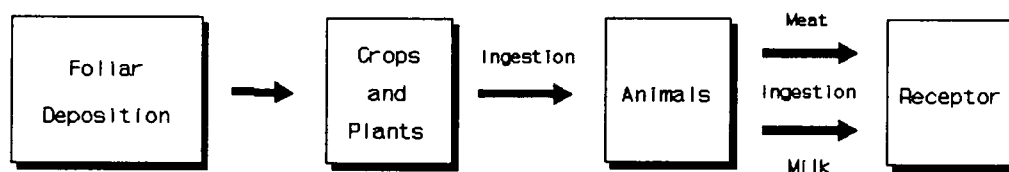


Figure B.11. Foliar Deposition Subpathway.

The ETF for the foliar deposition subpathway of the plant ingestion pathway is given by the following equation,

$$ETF_{i(4,5)2}(t) = FA_{i(4,5)} \times FCD_{i(4,5)2}(t) \times DF_{i(4,5)} \times FSR_{i(4,5)2} \quad (B.30)$$

The area factor is given by Eq. B.23. The dietary factors are given in Table 4.9. The cover and depth factor for the foliar deposition subpathway is the same as that for the dust inhalation pathway given by equation B.5. The food/source concentration ratios for the meat and milk ingestion, root uptake subpathway, $FSR_{i(4,5)2}$, are given by the following equation:

$$FSR_{i(4,5)2} = FQR_{i(4,5)} \times FI_{(4,5)2} \times QSR_{i(4,5)2}(t) \quad (B.31)$$

where,

FQR_{i4} and FQR_{i5} are both given by Table D.4 in the RESRAD manual, and

$$FI_{42} = 68 \text{ kg/d and } FI_{52} = 55 \text{ kg/d.}$$

The formulas for the fodder/soil concentration ratios for root uptake are as follows.

$$QSR_{i42} = QSR_{i52} = FA_2 \times FAR_{i323} \times ASR_3 \quad (B.32)$$

is the ratio for foliar deposition on fodder, where FA_2 is an area factor defined by equation B.7, ASR_3 is the air/soil concentration ratio defined in equation B.3, and FAR_{i323} is the plant-food/air concentration ratio defined by Eq. B.17.

B.3.2.2.3 Ditch Irrigation Subpathway

The ditch irrigation subpathway involves radionuclides deposited upon crops and plants from contaminated groundwater that is used as irrigation. The crops and plants are subsequently consumed by livestock. Fig. B.12 illustrates this subpathway.

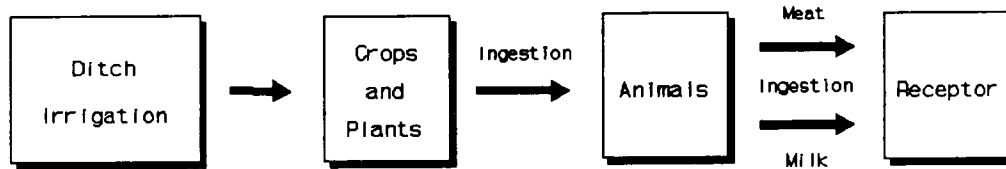


Figure B.12. Ditch Irrigation Subpathway.

The ETF for this subpathway is given by the following equation,

$$ETF_{i(4,5)3}(t) = FA_{(4,5)} \times FCD_{i(4,5)3}(t) \times DF_{(4,5)} \times FSR_{i(4,5)3} \quad (B.33)$$

The area factor is given by equation B.23. The dietary factors are given in Table E.9. The cover and depth factor for the ditch irrigation subpathway is given by equation the following equation,

$$FCD_{(4,5)3}(t) = 1 \quad (B.34)$$

The food/source concentration ratios for the meat and milk ingestion, root uptake subpathway, $FSR_{i(4,5)3}$, are given by the following equation,

$$FSR_{i(4,5)3} = FQR_{i(4,5)} \times FI_{(4,5)3} \times QSR_{i(4,5)3}(t) \quad (B.35)$$

where,

FQR_{i4} and FQR_{i5} are both given by Table E.5,

$FI_{43} = 68 \text{ kg/d}$ and $FI_{53} = 55 \text{ kg/d}$, and

$QSR_{i43}(t) = QSR_{i53}(t)$

$$QSR_{i43}(t) = QSR_{i53} = FWR_{i333} \times [WSR_{i1}(t) \times FI_1 + WSR_{i2}(t) \times (1 - FI_1)] \quad B.36$$

Eq B.36 is the ratio for ditch irrigation of fodder, where FWR_{i333} is the plant-food/water concentration ratio given by Eq. 4.41; $WSR_{i1}(t)$ and WSR_{i2} are the water/soil

concentration ratios for well water and surface water, respectively, as derived in Appendix D; and FI_1 is as defined for Eq. B.20.

B.3.2.2.4 Cattle Watering Subpathway

The cattle watering subpathway of the meat and milk ingestion pathways result from the ingestion of contaminated water by livestock. This subpathway is illustrated in Fig. B.13.

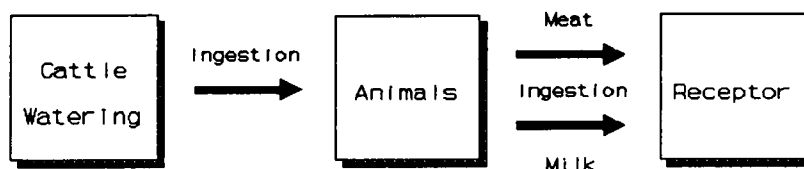


Figure B.13. Cattle Watering Subpathway.

The ETF for the cattle watering subpathway is given by the following equation,

$$ETF_{i(4,5)5}(t) = FA_{(4,5)} \times FCD_{i(4,5)5}(t) \times DF_{(4,5)} \times FSR_{i(4,5)5} \quad (B.37)$$

The area factor is given by Eq. 4.43. The dietary factors are given in Table 4.9. The cover and depth factor for the cattle watering subpathway is given by equation the following equation,

$$FCD_{(4,5)5} = 1 \quad (B.38)$$

The food/source concentration ratios for the meat and milk ingestion, root uptake subpathway, $FSR_{i(4,5)4}$, are given by the following equation,

$$FSR_{i(4,5)4} = FQR_{i(4,5)} \times FI_{(4,5)4} \times QSR_{i(4,5)4}(t) \quad (B.39)$$

where,

FQR_{i4} and FQR_{i5} are both given by Table E.9,

$FI_{45} = 50 \text{ L/d}$ and $FI_{55} = 160 \text{ L/d}$, and

$$QSR_{i45}(t) = QSR_{i55}(t) = WSR_{i1} \times FL_1 + WSR_{i2}(t) \times (1 - FL_1) \quad (\text{B.40})$$

$QSR_{i45}(t)$ is the ratio for intake of contaminated livestock water, where FL_1 is the fraction of well water used for feeding livestock (balanced from surface water; 1.0, dimensionless).

B.3.2.3 Fish Pathway

The fish ingestion pathway results from the consumption of fish from a nearby contaminated pond by the receptor. This pathway is illustrated by Fig. B.14.

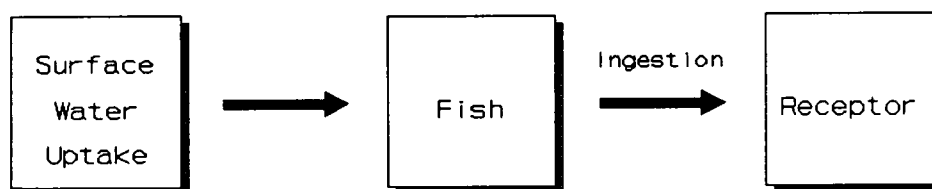


Figure B.14. Fish Ingestion Pathway.

The ETF for the aquatic food pathway ($p=6$) is given by the following equation,

$$ETF_{i6}(t) = FR_6 \times \left[\sum_k DF_{6k} \times FWR_{i6k} \right] \times WSR_{i2}(t) \quad (\text{B.41})$$

where the summation is over the aquatic food classes (see Table E.6) and

$ETF_{i6}(t)$ = ETF for the aquatic food pathway (fish, crustacea, and mollusks)(g/yr)

DF_{6k} = dietary factors for annual consumption of fish ($k=1$) and crustacea and mollusks ($k=2$)(kg/yr)

FR_6 = fraction of aquatic food consumed that

FWR_{i6k} = fish/water ($k=1$) and crustacea-mollusk/water ($k=2$) concentration ratios (bioaccumulation factors)(L/kg), and

$WSR_{i2}(t)$ = water/soil concentration ratio for surface water (g/L) (Yu, 1992).

Dietary factors are given in Table E.6 and bioaccumulation factors are given in Table E.9 in Appendix E. The water/soil concentration ratio for surface water is calculated using the hydrological data and assumptions described in Chapter 3.

The ETFs may also be written as products of a water exposure factor and a water/soil concentration ratio,

$$ETF_{i6}(t) = WEF_{i6} \times WSR_{i2}(t) \quad (B.42)$$

B.3.2.4 Drinking Water Pathway

The drinking-water ingestion pathway results from the consumption of contaminated groundwater withdrawn from a well. Fig. B.15 illustrates this pathway.



Figure B.15. Drinking Water Ingestion Pathway.

The equation for the ETFs for the drinking water pathway is given by the following equation,

$$ETF_{i7}(t) = DF_7 \times FDW \times [WSR_{i1}(t) \times FD_1 + WSR_{i2}(t) \times (1 - FD_1)] \quad (B.43)$$

where,

$ETF_{i7}(t)$ = ETFs for the drinking water pathway (g/yr),

- $DF_7 =$ annual intake of drinking water (510 L/yr),
 $FDW =$ fraction of drinking water from site (dimensionless),
 $WSR_{i1}(t) =$ water/soil concentration ratios for well water (g/L)
 $WSR_{i2}(t) =$ water/soil concentration ratios for surface water (g/L), and
 $FD_1 =$ fraction of well water used for drinking (balanced from surface water; 1.0, dimensionless) (Yu, 1992).

The annual intake of drinking water is a dietary factor from Table E.6. The water/soil concentration ratios are calculated using the models described in Appendix D.

B.3.2.5 Soil Ingestion Pathway

The soil ingestion pathway results from the ingestion of soil by the receptor. This pathway is illustrated by Fig. B.16.



Figure B.16. Soil Ingestion Pathway.

"The ETF for soil ingestion is the ratio of the annual intake $E_{j8}(t)$ of the j th principal radionuclide by soil ingestion to the concentrations $S_j(t)$ of the of radionuclide in the soil, that is, $ETF_{j8}(t) = E_{j8}(t) / S_j(t)$ " (Yu, 1992). The ETF is given by the following equation,

$$ETF_{j8}(t) = FSI \times FA_8 \times FCD_8(t) \times FO_8 \quad (B.44)$$

where,

FSI = Annual intake of soil (g/yr),

FA₈ = Area Factor (dimensionless),

FCD₈(t) = Cover and depth factor (dimensionless), and

FO₈ = Occupancy factor (dimensionless).

The annual intake of soil depends on the age group. EPA suggests that a value of 70 g/yr (200 mg/d) can be used as an average value for young children (under the age of 7); for other age groups (older than 7 years old), the average value is 35 g/yr (100 mg/d), which accounts for intakes of both outdoor soil and indoor dust (Yu, 1992).

The default soil ingestion rate of 36.5 g/yr (100 mg/d) is used for all of the contaminated zone areas.

"The area factor represents the fraction of the playing or working area that might be contaminated" (Yu, 1992). It is given by the following relationship,

$$FA_8 = \begin{matrix} A/1000, & 0 < A < 1000 \text{ m}^2 \\ = & 1 & A > 1000 \text{ m}^2 \end{matrix} \quad (B.45)$$

where,

A = the area of the contaminated zone.

The cover and depth factor and the occupancy factor are the same as those for the inhalation pathway.

APPENDIX C

RADIOLOGICAL SURVEYS OF THE ROCKY FLATS PLANT AND SURROUNDING AREA

C.1 Radiological Surveys

Two surveys were used to characterize plutonium and americium soil concentrations in the three contaminated areas. The 1990 *1991 In Situ Survey* is used for the on-site area and the 1991 Annual Remedy Acreage Survey is used for both off-site areas. The following sections describe the surveys and present the results.

C.1.1 *1991 In Situ Survey*

The Remote Sensing Laboratory (RSL) of EG&G Energy Measurements conducted several in situ radiological surveys at RFP in 1990, including one at the Old Landfill area from October 25 through November 7, and one at the area east of the 903 Pad from November 8 through December 8. These two survey areas are shown in Fig. C.1.

The Old Landfill and the area east of the 903 Pad were sampled using a 46-m (150-ft) grid pattern. The survey grid was established using an electronic distance meter with an electronic theodolite. Stakes were left to mark each surveyed location and were labeled with the grid location and the Colorado Grid coordinates. ". . . Sampling locations were tied to the Colorado Grid Coordinate System by way of a plant site map provided by Rocky Flats personnel and by referencing a station, 'ENERGY,' placed by a previous National Oceanic and Atmospheric Administration (NOAA) survey. The positional accuracy to the sample locations was estimated to be better than ± 3 m (10 ft)" (EG&G EM, 1991).

Two high purity germanium (HPGe) gamma ray detectors were used to make

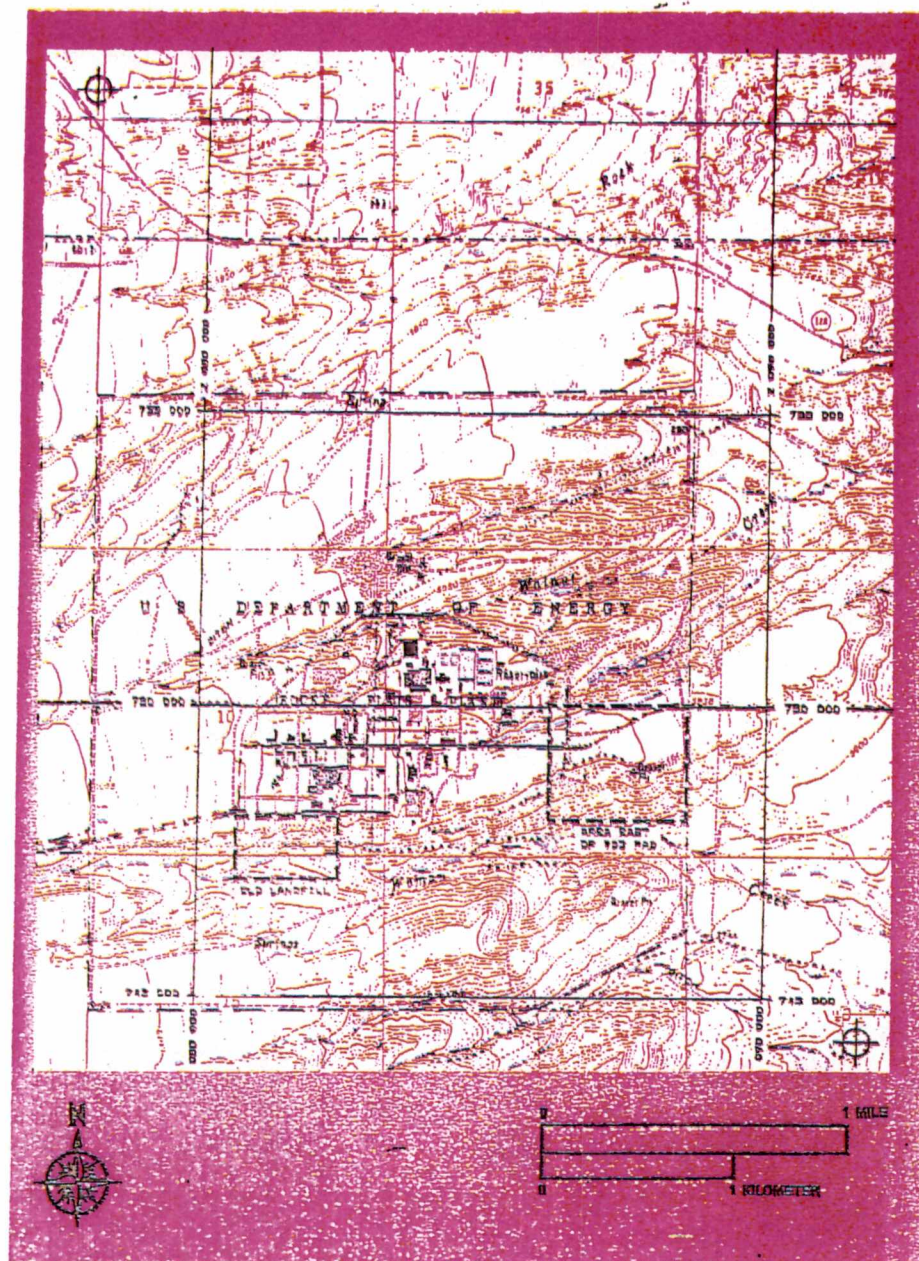


Figure C.1. Rocky Flats Plant Site Map

Source: "In Situ Surveys of the United States Department of Energy's Rocky Flats Plant," EG&G Energy Measurements, May 1991.

several ground-based in situ measurements. The detectors were nominally 20%, N-type, coaxial detectors, and each was mated with multichannel pulse height analyzers. One detector was placed one meter above the ground on a tripod. The other detector was suspended 7.5 m above the ground by a pneumatic telescoping mast that was mounted to a vehicle. Gamma ray data were collected as an energy spectrum over a 900-second interval and analyzed with the NUClear Material Analysis program (NuMAI), a germanium, gamma ray spectrum, peak search computer program. NuMAI produced results in the form of radionuclide concentration in the soil (EG&G EM, 1991).

Figure C.2 illustrates the sampling grid used for the *1991 In Situ Survey*.

C.1.2 Remedy Acreage Annual Survey

The CDH performed annual surveys for plutonium in the Remedy Acreage from 1970 to 1989. The results of these surveys are listed in Table 2.2 of the *Final RFI/RI Work Plan for OU 3*. The number of data points ranged from 5 to 13 with the majority of surveys consisting of 13. Because previously taken soil samples do not meet current quality assurance protocols, the CDH collected samples in January 1991 from both tilled and untilled soil.

C.2 Radiological Survey Results

C.2.1 1991 In Situ Survey Results

Isoconcentration Contours for Am-241 (pCi/g) for the areas east of the 903 Pad are shown in Fig. C.3. Table C.1 presents the results for the individual locations based on the Colorado Grid Coordinate System. These results are given in pCi/gr and are based on a homogenous, three-dimensional distribution of the species within the soil matrix and averaged over the top 3 cm of soil. The data presented in Table C.1 overlies an isoconcentration contour map for Am-241 (pCi/g) in Fig. C-4. Pu-239, -240 activity



Figure C.2. Area East of the 903 Pad Grid Survey Map

"In Situ Surveys of the United States Department of Energy's Rocky Flats Plant," EG&G Energy Measurements, May 1991.

Source:





Figure C.3. Area East of the 903 Pad Americium-241
(pCi/g) Isoconcentration Contours

"In Situ Surveys of the United States Department of Energy's Rocky Flats Plant," EG&G Energy Measurements, May 1991.

Source:

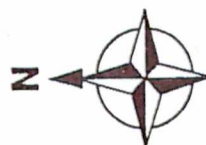


Table C.1. 1991 In Situ Survey Results for Area East of 903 Pad

Stake	Coordinates		Am-241 Surface Concentration (pCi/g)
	North	East	
A,1	749925	2086582	
A,2	749925	2086732	1.4
A,3	749925	2086882	1.8
A,4	749925	2087032	2.2
A,5	749925	2087182	2.2
A,6	749925	2087332	1.6
A,7	749925	2087482	1.7
A,8	749925	2087632	1.1
A,9	749925	2087782	
A,10	749925	2087932	
A,11	749925	2088082	0.9
A,12	749925	2088232	1.8
A,13	749925	2088382	2.1
A,14	749925	2088532	0.9
B,1	749775	2086582	1.0
B,2	749775	2086732	2.8
B,3	749775	2086882	2.8
B,4	749775	2087032	2.4
B,5	749775	2087182	1.2
B,6	749775	2087332	1.3
B,7	749775	2087482	1.4
B,8	749775	2087632	
B,9	749775	2087782	2.3
B,10	749775	2087932	3.6
B,11	749775	2088082	2.4
B,12	749775	2088232	1.3

Table C.1. (continued)

Stake	Coordinates		Am-241 Surface Concentration (pCi/g)
	North	East	
B,13	749775	2088382	1.5
B,14	749775	2088532	0.8
C,1	749625	2086582	8.1
C,1	749625	2086582	8.1
C,2	749625	2086732	6.3
C,3	749625	2086882	2.6
C,4	749625	2087032	1.7
C,5	749625	2087182	1.5
C,6	749625	2087332	
C,7	749625	2087482	1.5
C,8	749625	2087632	5.2
C,9	749625	2087782	4.8
C,10	749625	2087932	3.1
C,11	749625	2088082	2.3
C,12	749625	2088232	2.5
C,13	749625	2088382	0.9
C,14	749625	2088532	1.2
D,1	749475	2086582	
D,2	749475	2086732	7.2
D,3	749475	2086882	14.0
D,4	749475	2087032	5.0
D,5	749475	2087182	5.7
D,6	749475	2087332	10.0
D,7	749475	2087482	6.0
D,8	749475	2087632	10.0
D,9	749475	2087782	7.8

Table C.1. (continued)

Stake	Coordinates		Am-241 Surface Concentration (pCi/g)
	North	East	
D,10	749475	2087932	6.0
D,11	749475	2088082	4.3
D,12	749475	2088232	2.9
D,13	749475	2088382	1.2
D,14	749475	2088532	0.8
E,1	749325	2086582	
E,2	749325	2086732	1.9
E,3	749325	2086882	10.0
E,4	749325	2087032	20.0
E,5	749325	2087182	18.0
E,6	749325	2087332	13.0
E,7	749325	2087482	8.1
E,8	749325	2087632	6.1
E,9	749325	2087782	6.8
E,10	749325	2087932	8.3
E,11	749325	2088082	6.8
E,12	749325	2088232	4.5
E,13	749325	2088382	1.2
E,14	749325	2088532	
F,1	749175	2086582	17.0
F,1			20.0
F,2	749175	2086732	32.0
F,3	749175	2086882	19.0
F,4	749175	2087032	19.0
F,5	749175	2087182	19.0
F,6	749175	2087332	11.0

Table C.1. (continued)

Stake	Coordinates		Am-241 Surface Concentration (pCi/g)
	North	East	
F,7	749175	2087482	4.2
F,8	749175	2087632	1.2
F,9	749175	2087782	
F,10	749175	2087932	2.0
F,11	749175	2088082	0.9
F,12	749175	2088232	0.9
F,13	749175	2088382	1.1
F,14	749175	2088532	0.8
G,1	749025	2086582	82.0
G,1			100.0
G,2	749025	2086732	27.0
G,3	749025	2086882	8.3
G,4	749025	2087032	34.0
G,5	749025	2087182	18.0
G,6	749025	2087332	19.0
G,7	749025	2087482	18.0
G,8	749025	2087632	0.8
G,9	749025	2087782	
G,10	749025	2087932	
G,11	749025	2088082	
G,12	749025	2088232	2.9
G,13	749025	2088382	3.7
G,14	749025	2088532	2.1
H,1	748875	2086582	39.0
H,1			35.0
H,2	748875	2086732	28.0
H,3	748875	2086882	14.0

Table C.1. (continued)

Stake	Coordinates		Am-241 Surface Concentration (pCi/g)
	North	East	
H,4	748875	2087032	7.6
H,5	748875	2087182	4.0
H,6	748875	2087332	10.0
H,7	748875	2087482	14.0
H,8	748875	2087632	1.2
H,9	748875	2087782	
H,10	748875	2087932	1.3
H,11	748875	2088082	5.7
H,12	748875	2088232	5.7
H,13	748875	2088382	3.5
H,14	748875	2088532	2.4
I,-1	748725	2086432	30.0
I,1	748725	2086582	25.0
I,1			22.0
I,2	748725	2086732	16.0
I,3	748725	2086882	13.0
I,4	748725	2087032	2.0
I,5	748725	2087182	5.8
I,6	748725	2087332	6.4
I,7	748725	2087482	7.8
I,8	748725	2087632	5.3
I,9	748725	2087782	3.1
I,10	748725	2087932	4.2
I,11	748725	2088082	4.8
I,12	748725	2088232	3.4
I,13	748725	2088382	2.2

Table C.1. (continued)

Stake	Coordinates		Am-241 Surface Concentration (pCi/g)
	North	East	
I,14	748725	2088532	1.3
J,-1	748575	2086432	24.0
J,1	748575	2086582	18.0
J,2	748575	2086732	16.0
J,3	748575	2086882	12.0
J,4	748575	2087032	8.1
J,5	748575	2087182	5.5
J,6	748575	2087332	4.9
J,7	748575	2087482	4.5
J,8	748575	2087632	3.6
J,9	748575	2087782	3.7
J,10	748575	2087932	3.1
J,11	748575	2088082	3.4
J,12	748575	2088232	2.3
J,13	748575	2088382	1.8
J,14	748575	2088532	
K,-2	748425	2086282	8.4
K,-1	748425	2086432	15.0
K,1	748425	2086582	11.0
K,2	748425	2086732	12.0
K,3	748425	2086882	9.0
K,4	748425	2087032	6.1
K,5	748425	2087182	5.7
K,6	748425	2087332	3.8
K,7	748425	2087482	1.5
K,8	748425	2087632	2.7

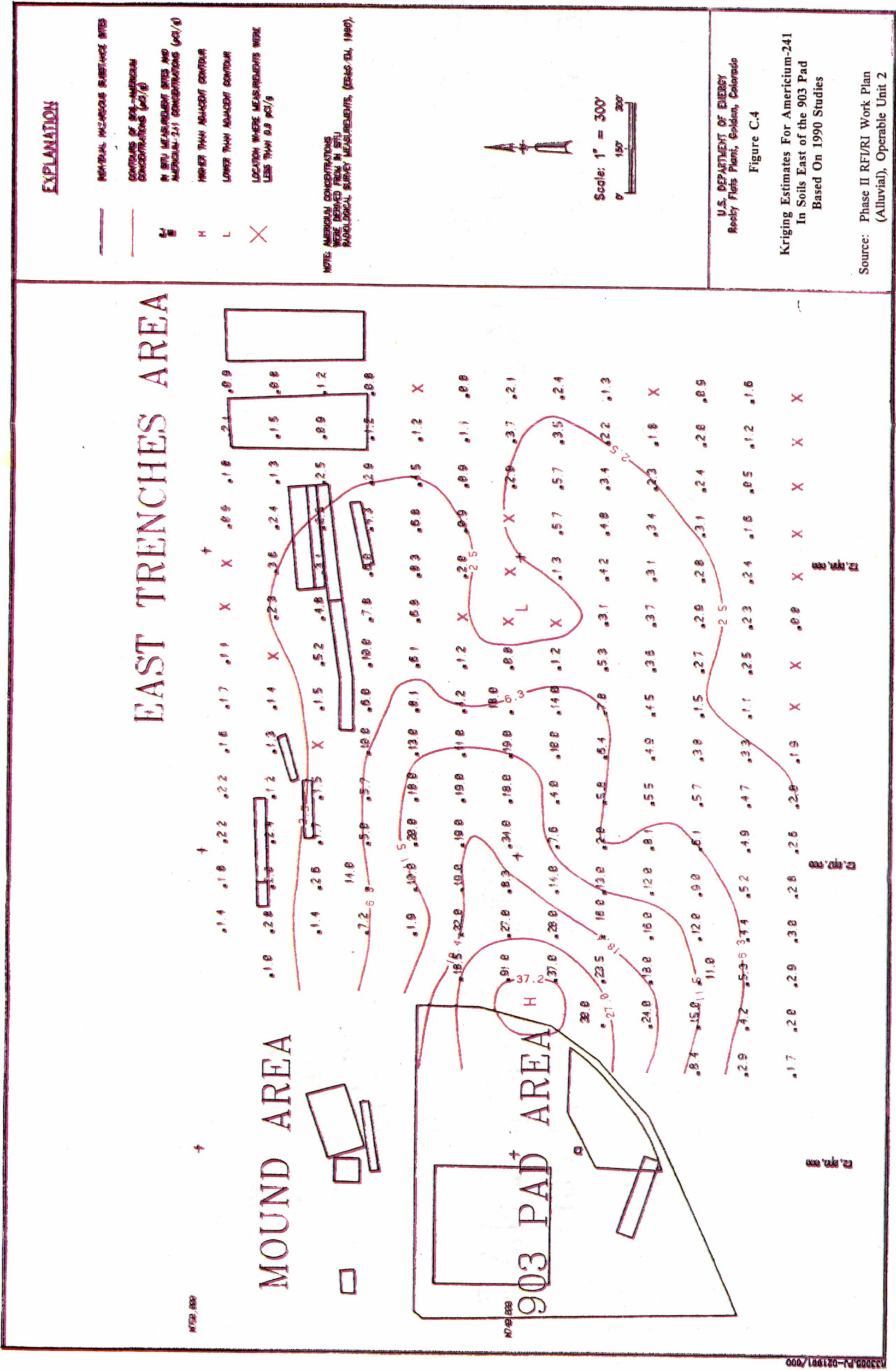
Table C.1. (continued)

Stake	Coordinates		Am-241 Surface Concentration (pCi/g)
	North	East	
K,9	748425	2087782	2.9
K,10	748425	2087932	2.8
K,11	748425	2088082	3.1
K,12	748425	2088232	2.4
K,13	748425	2088382	2.0
K,14	748425	2088532	0.9
L,-2	748275	2086282	2.9
L,-1	748275	2086432	4.2
L,1	748275	2086582	5.3
L,2	748275	2086732	4.4
L,3	748275	2086882	5.2
L,4	748275	2087032	4.9
L,5	748275	2087182	4.7
L,6	748275	2087332	3.3
L,7	748275	2087482	1.1
L,8	748275	2087632	2.5
L,9	748275	2087782	2.3
L,10	748275	2087932	2.4
L,11	748275	2088082	1.6
L,12	748275	2088232	0.5
L,13	748275	2088382	1.2
L,14	748275	2088532	1.6
M,-2	748125	2086282	1.7
M,-1	748125	2086432	2.0
M,1	748125	2086582	2.9
M,2	748125	2086732	3.0

Table C.1. (continued)

Stake	Coordinates		Am-241 Surface Concentration (pCi/g)
	North	East	
M,3	748125	2086882	2.8
M,4	748125	2087032	2.6
M,5	748125	2087182	2.8
M,6	748125	2087332	1.9
M,7	748125	2087482	
M,8	748125	2087632	
M,9	748125	2087782	0.8
M,10	748125	2087932	
M,11	748125	2088082	
M,12	748125	2088232	
M,13	748125	2088382	
M,14	748125	2088532	

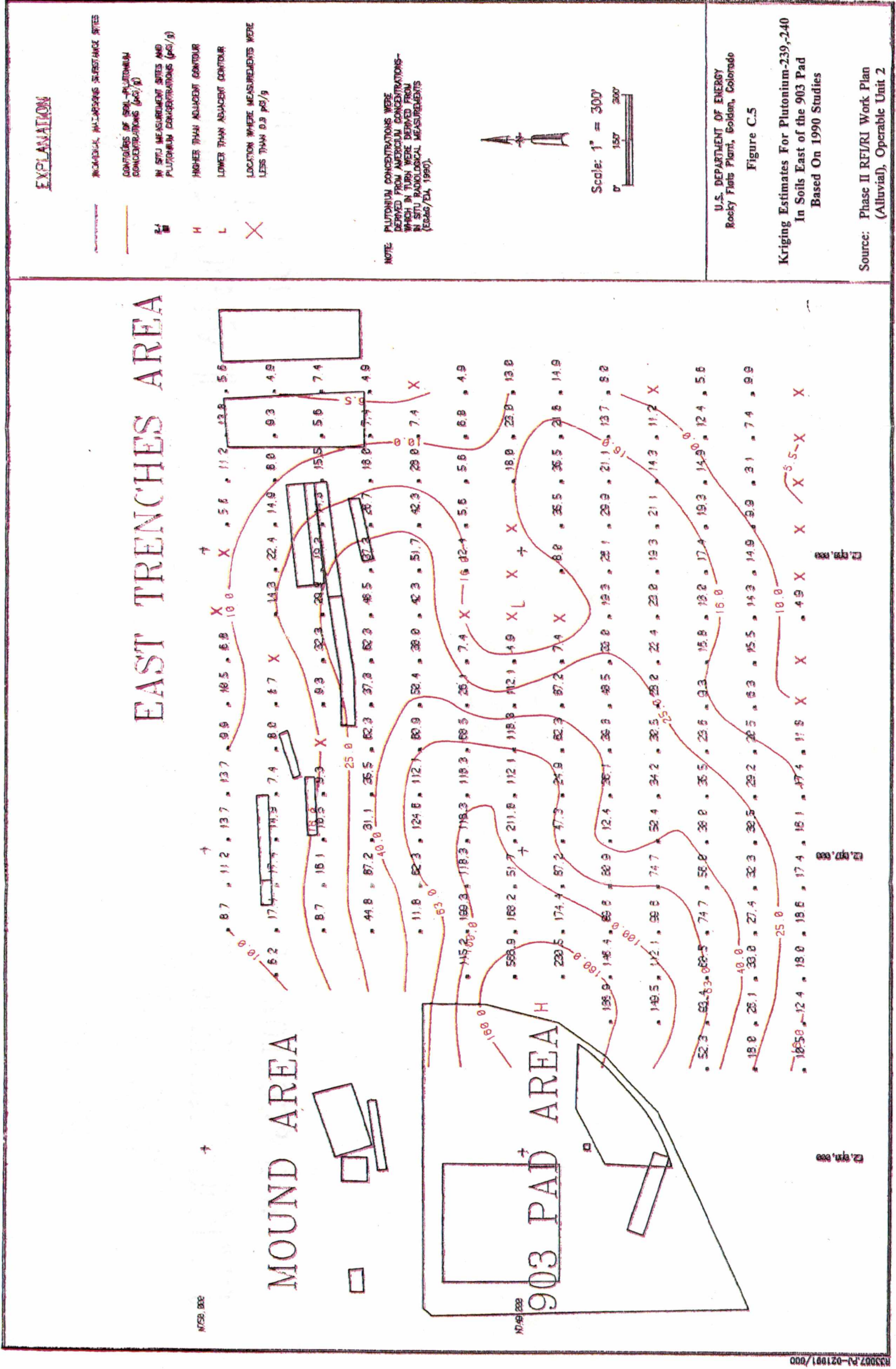
Source: 1991 *In Situ* Survey of the United States Department of Energy's Rocky Flats Plant

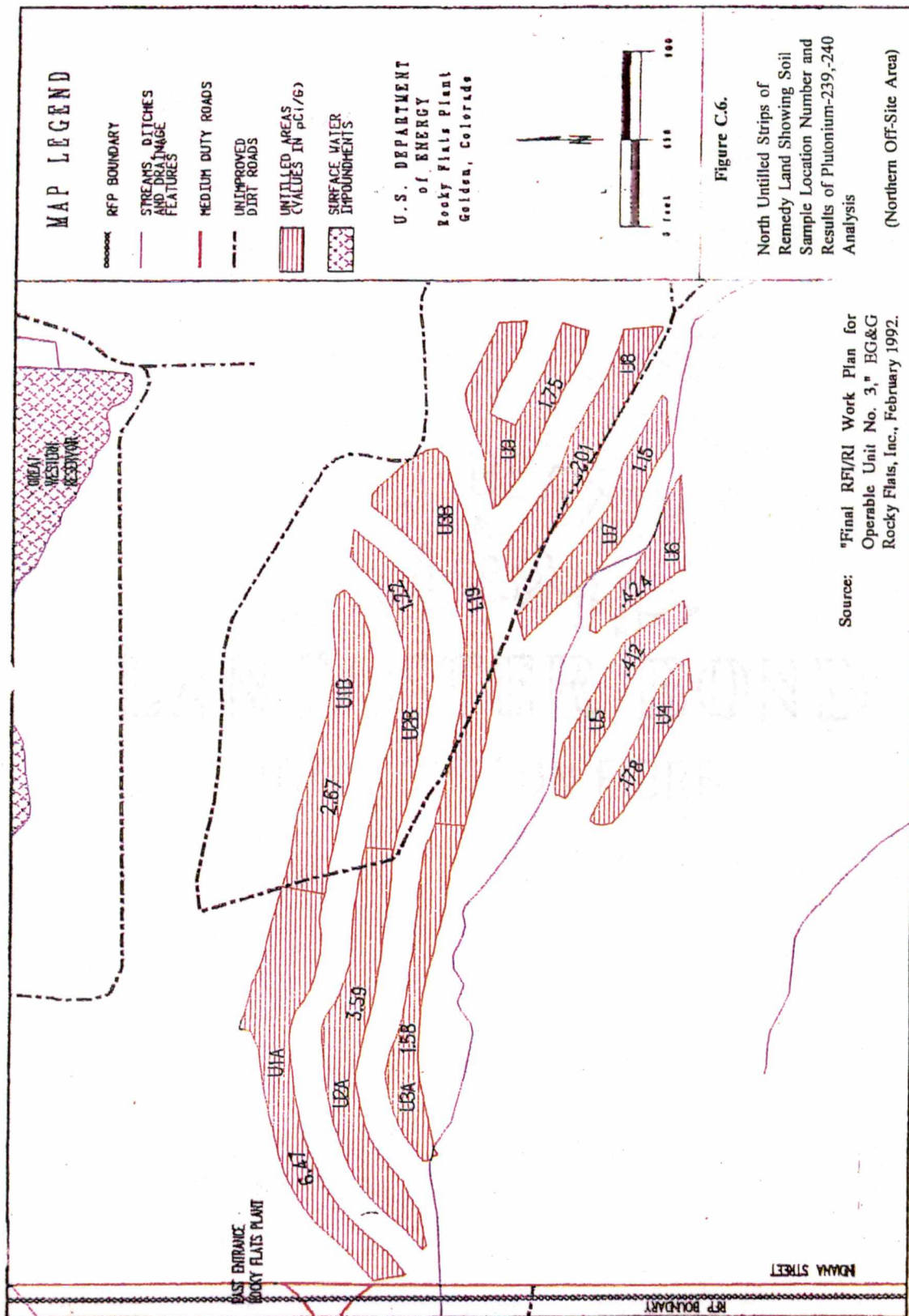


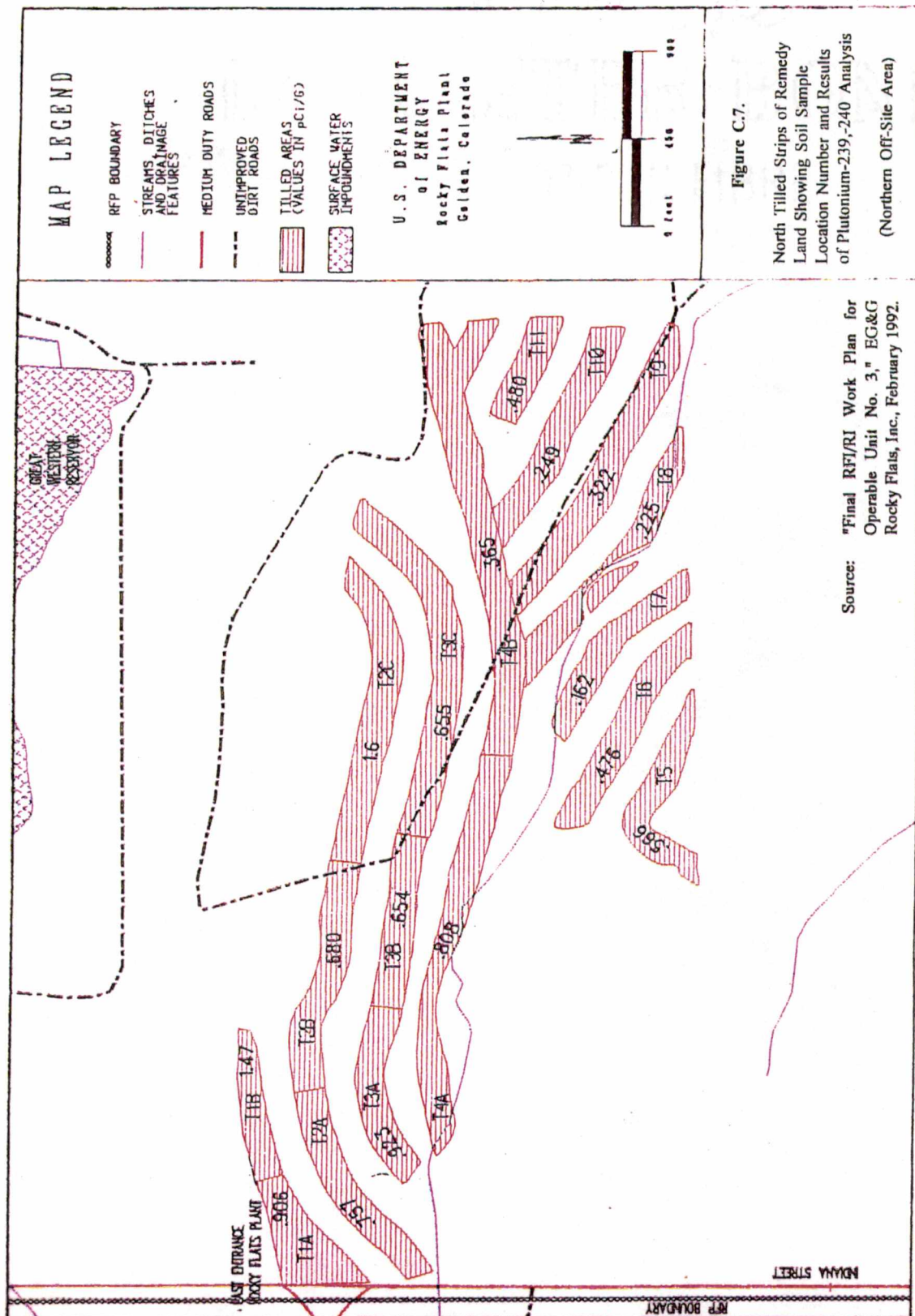
concentrations are calculated by multiplying the respective Am-241 concentrations by a ratio factor. The *1991 In Situ Survey* calculated an activity ratio factor of 6.23. Fig. C.5 presents the Pu-239, -240 activity concentration data derived from the data in Table C.1 using this ratio factor.

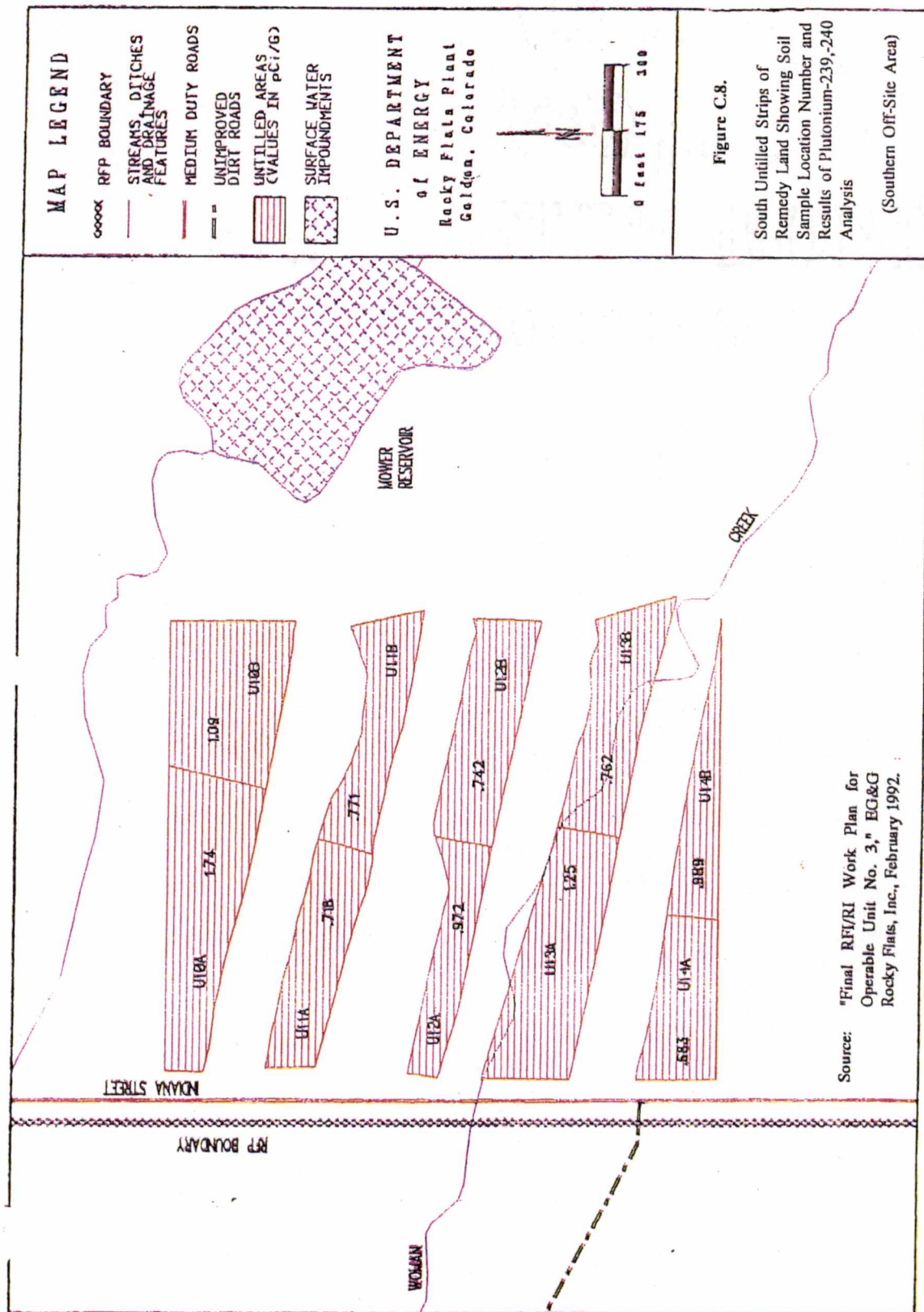
C.2.2 Results of the 1991 Remedy Acreage Annual Survey

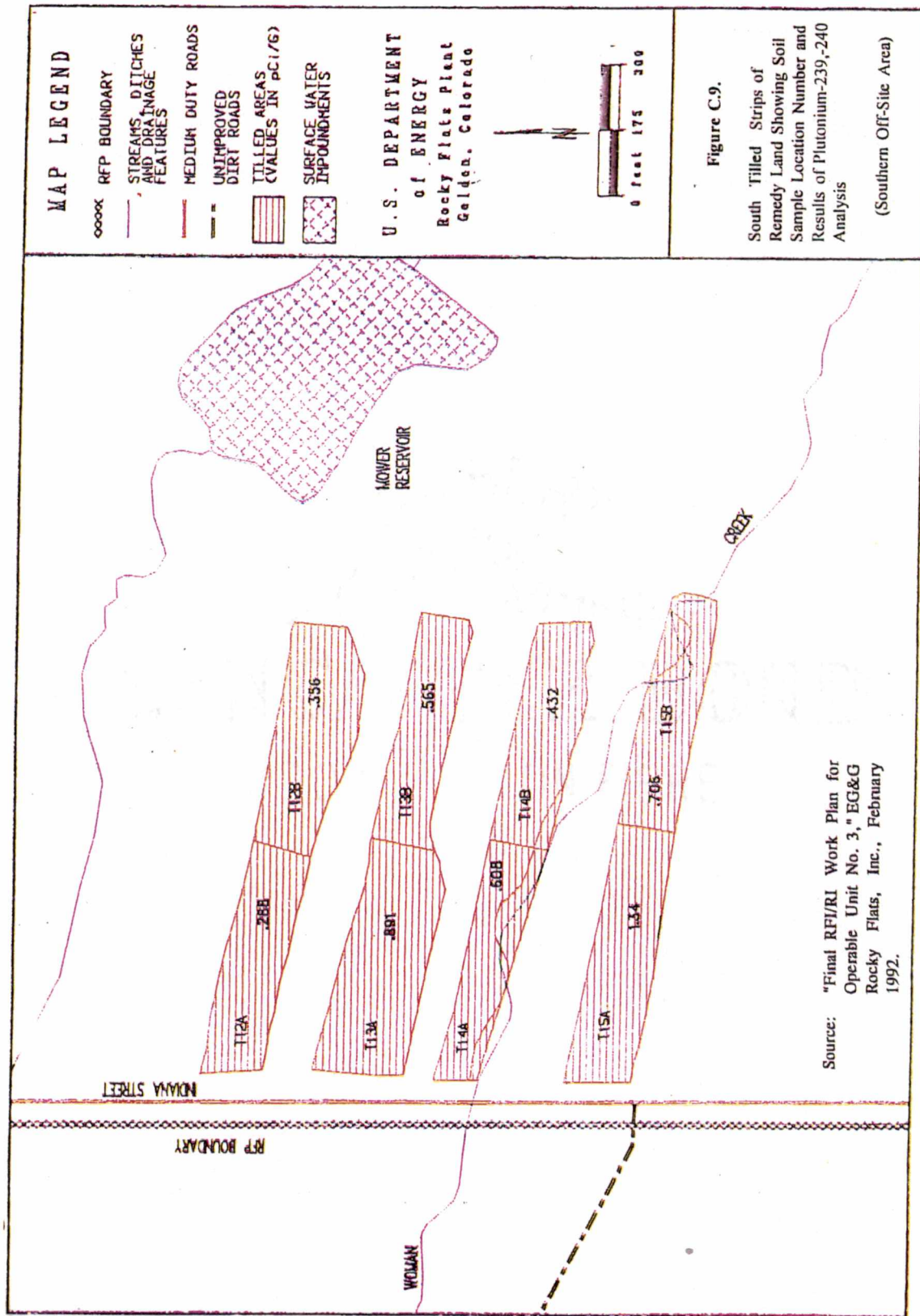
The samples taken from the Remedy Acreage by the CDH were analyzed for plutonium and americium. The results of this survey for plutonium-239 and -240 are shown in Figs. C.6 through C.9.











APPENDIX D

RADIONUCLIDE LEACHING MODEL

D.1 Radionuclide Leaching from the Contaminated Zone

Radionuclides absorbed in soil are subject to leaching by infiltrating water. This leachate is the source for groundwater contamination. "Therefore, the first step in calculating radionuclide concentrations in groundwater is to estimate the leaching of radionuclides from the contaminated zone" (Yu, 1992). This appendix describes the radionuclide leaching model used in RESRAD. All of the equations, relationships, and the descriptions of variables are from the RESRAD manual.

"An adsorption-desorption, ion-exchange leaching model is used in the RESRAD code. This model is characterized by a nuclide-dependent, first-order leach rate constant, L_i , which is defined as the fraction of available radionuclide i leached out per unit time (t)" (Yu, 1992).

The RESRAD manual defines the radionuclide release rate (source strength, in Ci/yr), $R_i(t)$, in the following equation,

$$R_i(t) = L_i \times \rho_b^{(cz)} \times A \times T(t) \times S_i(t) \quad (D.1)$$

where,

$L_i =$	leach rate for radionuclide i (yr. ⁻¹),
$\rho_b^{(cz)} =$	bulk density of the contaminated zone (kg/m ³),
$A =$	area of the contaminated zone (m ²),
$T(t) =$	thickness of the contaminated zone at time t (m), and
$S_i(t) =$	average concentration of the i th principal radionuclide in the contaminated zone available for leaching at time t (pCi/kg).

"The first-order leach rate constant used in the current version of RESRAD is a time-dependent radionuclide leach rate constant that is estimated based on the soil residence time for the initial thickness of the contaminated zone." The time-dependent radionuclide leach rate constant for radionuclide i , $L_i(t)$, is given by the following equation,

$$L_i(t) = \frac{1}{\theta^{(cz)} T(t) R_{di}^{(cz)}} \quad (D.2)$$

where,

I = infiltration rate (m/yr),

$\theta^{(cz)}$ = volumetric water content of the contaminated zone, and

$R_{di}^{(cz)}$ = retardation factor in the contaminated zone for radionuclide i (dimensionless)

The infiltration rate is calculated by the following equation,

$$I = (1 - C_e)[(1 - C_r)P_r + I_{rr}] \quad (D.3)$$

where,

C_e = evapotranspiration coefficient (dimensionless),

C_r = runoff coefficient (dimensionless),

P_r = precipitation rate (annual rainfall), and

I_{rr} = irrigation rate (m/yr).

The average evapotranspiration coefficient is used to calculate the infiltration rate rather than the average evapotranspiration rate. "Using the average evapotranspiration rate does not take into account the correlation between precipitation and evapotranspiration and, for arid regions, can give a spurious negative infiltration rate" (Yu, 1992). The evapotranspiration coefficient is related to the evapotranspiration rate by the

following formula,

$$C_e = \frac{E_t}{[(I - C_r)P_r + I_m]} \quad (D.4)$$

Runoff coefficients for a specific site may be obtained from Table E.1 in the RESRAD Manual. "It is assumed that irrigation water is controlled by ditching or by the duration of application so that none will be lost by runoff" (Yu, 1992).

The volumetric water content of the contaminated zone, $\theta^{(cz)}$, is the product of the saturated water content of the contaminated zone, $\theta_{sat}^{(cz)}$, and the saturation ratio of the contaminated zone, $R_s^{(cz)}$. The saturated water content is the water content when the soil material is saturated. Hence, $\theta^{(cz)}$ equals p_t , where p_t is the total porosity of the soil material, that is

$$\theta^{(cz)} = p_t \quad (D.5)$$

The saturation ratio, R_s , is defined as the ratio of θ over θ_{sat} , that is,

$$R_s = \frac{\theta}{\theta_{sat}} = \frac{\theta}{p_t} \quad (D.6)$$

When the median is saturated, R_s equals unity. Under unsaturated infiltration conditions, the saturation ratio is a function of the infiltration rate, the saturated hydraulic conductivity, and the texture of the soil (Yu, 1992).

The saturation ratio is given by the following equation,

$$R_s = \left(\frac{I}{K_{sat}} \right)^{\left[\frac{1}{(2b+3)} \right]} \quad (D.7)$$

where,

I = infiltration rate (m/yr),

K_{sat} = saturated hydraulic conductivity (m/yr), and

b = soil-specific exponential parameter (dimensionless).

The retardation factor for radionuclide i , R_{di} , is the ratio of average pore water velocity to radionuclide transport velocity. Assuming that the absorption-desorption process can be represented with a linear Freundlich isotherm, the retardation factor can be calculated with the formula,

$$R_{di} = 1 + \frac{[p_b K_{di}]}{\theta} = 1 + \frac{[p_b K_{di}]}{[p_i R_d]} \quad (D.8)$$

where,

- p_b = bulk soil density (g/cm³),
- K_{di} = distribution coefficient for the i th principal radionuclide (cm³/g), and
- θ = volumetric water content (dimensionless).

The distribution coefficient is the radionuclide equilibrium concentration ratio of the absorbed radionuclide (in soil) to the desorbed radionuclide (in water) (Yu, 1992).

D.2 Water/Soil Concentration Ratios in Terms of Nuclide Water-Transport Parameters

"A water/soil concentration ratio can be expressed in terms of functions that characterize the source terms and transport processes and are applicable for both simple and complex hydrogeological strata" (Yu, 1992). Using approximations for the functional form of the breakthrough curve (the concentration of a radionuclide in water at the point of use as a function of time), the transport and source functions can be specified by a small number of nuclide water-transport parameters. Various models can be used to derive relations between these parameters and measurable quantities and the analysis is applicable to either the groundwater or surface water pathways (Yu, 1992).

The water/soil concentration ratio is derived in Appendix E.2 of the RESRAD manual. The general expression for the water/soil concentration ratio is given by the following equation,

$$WSR_i(t) = \frac{\rho_b^{(cz)}}{\theta^{(cz)} L_{ji}(t)} \int_0^t g_i(t-t') Q_i(t') L_{ji}(t') dt' \quad (D.9)$$

Equation D.9 is used for deriving formulas for estimating the concentrations of radionuclides in water used for drinking or irrigation (Yu, 1992).

After correcting for radionuclide leaching, the time dependence of the water/soil concentration ratio for the ground water pathway is approximated by the following relationship,

when $t \leq \Delta t_i$,

$$WSR_{ir}(t) = 0 \quad (D.10)$$

when $\Delta t_i < t \leq \Delta t_i + \delta t_{ir}$,

$$WSR_{ir}(t) = \frac{\rho_b^{(cz)} f_{ir}}{\theta^{(cz)} R_{di}^{(cz)} \delta t_{ir} L_i} [1 - \exp^{-L_i(t - \Delta t_i)}]$$

and when $\Delta t_i + \delta t_{ir} < t$,

$$WSR_{ir}(t) = \frac{\rho_b^{(cz)} f_{ir}}{\theta^{(cz)} R_{di}^{(cz)} \delta t_{ir} L_i} [\exp^{-L_i(t - \Delta t_i - \delta t_{ir})} - \exp^{-L_i(t - \Delta t_i)}]$$

where the various parameters are as defined in Appendix E of the RESRAD manual.

If the rise time is negligibly small ($\delta t_{ir} = 0$), then Eq D.10 may be simplified to the following relationship,

when $t \leq \Delta t_i$,

$$WSR_{ir}(t) = 0 \quad (D.11)$$

and when $\Delta t_i < t$,

$$WSR_{ir}(t) = \frac{\rho_b^{(cz)} f_{ir}}{\theta^{(cz)} R_{di}^{(cz)}} \exp^{-L_i(t - \Delta t_i)}$$

Formulas for calculating the transport parameters (dilution factors, f_{ir} ; breakthrough times, Δt_i ; and rise times, δt_{ir}) for simple hydrogeological systems are derived in Section D.3.

D.3 Water Transport Parameters

Two water transport subpathways are considered by RESRAD.

Section D.3.1 discusses the groundwater transport subpathway and sect.

D.3.2 discusses the surface water transport subpathway.

D.3.1 On-Site Groundwater Transport Subpathway

The water transport parameters for radionuclide i are the breakthrough time Δt_i (the time following the radiological survey at which radionuclides first appear in the water at the point of use), the rise time δt_{ir} (the time following the breakthrough time for the radionuclide concentration in the water to attain a maximum value), and the dilution factor f_{ir} (the ratio between the concentration in the water at the point of use to the concentration in the infiltrating water as it leaves the contaminated zone). Two models are used for calculating these parameters: a mass-balance (MB) model and a nondispersion (ND) model. In the MB model, it is assumed that all of the radionuclides released from the contaminated zone are withdrawn through the well. In the ND model, it is assumed that the dispersity is nil, the unsaturated zone consists of one or more horizontal homogenous strata, the saturated zone is single homogenous stratum, and water withdrawal introduces only a minor perturbation in the water flow. These assumptions lead to a pattern of flow lines from which the dilution factor can be estimated by geometric considerations (Yu, 1992).

The MB model is suggested by the RESRAD manual for smaller contaminated areas (e.g., 1,000 m² or less), and the ND model is suggested for larger areas. Since all three of the contaminated areas assessed at RFP are considerably larger than 1,000 m²,

the nondispersion model is used. Breakthrough times are the same for either model, but the rise times and dilution factors are different (Yu, 1992). The breakthrough time is discussed in sect. D.3.1.1, the rise time is discussed in sect. D.3.1.2, and the dilution factor is discussed in sect. D.3.1.3.

D.3.1.1 Breakthrough Times

The breakthrough time is the length of time for the first unit of contamination to be transported through the unsaturated zone (in this assessment only one strata is considered for the unsaturated zone) to the point of use, which is assumed to be a well located at the downgradient edge of the contaminated zone. Radionuclides are assumed to enter the well as soon as they reach the water table. Thus, the transport time through the aquifer is nil and the breakthrough time is equal to the transport time through the unsaturated zone.

The transport time is calculated from the following equation,

$$\Delta t_i^{(uz)} = \frac{\Delta z R_i^{(uz)} p_e^{(uz)} R_s^{(uz)}}{I} \quad (D.12)$$

where,

- $\Delta z =$ thickness of the unsaturated zone (1 homogeous strata)
- $R_d^{(uz)} i =$ retardation factor of the i th principal radionuclide in the unsaturated zone,
- $p_e^{(uz)} =$ effective porosity of the unsaturated zone (dimensionless), and
- $R_s^{(uz)} =$ saturation ratio of the unsaturated zone (dimensionless).

The unsaturated zone retardation factor, $R_d^{(uz)} i$ is calculated by Eqn D.13,

$$R_{dim}^{(uz)} = \frac{1 + p_{bm}^{(uz)} K_{dim}^{(uz)}}{p_{bm}^{(uz)} R_{sm}^{(uz)}} \quad (D.28)$$

where,

$p^{(uz)}_b =$ bulk soil density for the unsaturated zone,

$K^{(uz)}_{di} =$ distribution coefficient for the i th principal radionuclide in the unsaturated zone (cm^3/g), and

$p^{(uz)}_t =$ total porosity of the m th stratum (dimensionless).

The saturation ratio, $R^{(uz)}$, can be determined by using Eq D.7.

Hydraulic conductivity and distribution coefficients are critical hydrological parameters that can differ by several orders of magnitude from one site to another. Default values are provided in the RESRAD manual. Distribution coefficients depend strongly on soil type, the pH and Eh of the soil, and the presence of other ions.... Thus, the uncertainty introduced by using default values for the distribution coefficients can be very large. This is a critical matter, especially in those cases where the water-dependent pathways are the dominant contributors to the total dose/source concentration ratios; the single-radionuclide soil guidelines will be directly proportional to the distribution coefficients for the contaminated zone. Default values for the distribution coefficients are provided only for the purpose of obtaining preliminary estimates; site-specific values should be used for deriving soil guidelines whenever possible" (Yu, 1992).

The distance from the ground surface to the water table, $D_{wt}(t)$, at time t is

$$D_{wt}(t) = C_d(t) + T(t) + \sum_{m=1}^{n+1} \Delta z_m^{uz} \quad (D.14)$$

where,

$C_d(t) =$ cover depth at time t (m),

$T(t) =$ thickness of contaminated zone at time t (m), and

$\Delta z_m =$ thickness of the m th stratum

In the current version of RESRAD, the water table is assumed to be below the contaminated zone, i.e., $D_{wt}(0) \geq C_d(0) + T(0)$ (for all three contaminated areas $C_d(0) = 0$).

D.3.1.2 Rise Time

Following breakthrough, the concentration of the i th radionuclide at the point of use will increase to a maximum and then decrease back to a near-zero value in a time interval δt_i . This time is referred to as the rise time because it is also the time for the contamination at the point of use to increase from zero to a maximum value when the pulse release is replaced by a steady release starting at the same time" (Yu, 1992). The rise time for the nondispersion model is given by the following formula,

$$\begin{aligned} \delta t_{i1} &= \tau_{ii}, & \zeta \leq d_w, D_{wt}(t) \geq C_d(t) + T(t) \\ &= \tau_{ii}/(\zeta/d_w), & \zeta > d_w, D_{wt}(t) \geq C_d(t) + T(t) \\ &= 0, & D_{wt}(t) < C_d(t) + T(t) \end{aligned} \quad (D.15)$$

$$\begin{aligned} \text{and, } \zeta &= (I/V_{wfr})l \\ V_{wfr} &= K^{(sz)}_x J_x \end{aligned}$$

where,

$$\begin{aligned} \zeta &= \text{distance from water table to lower boundary of contamination in the aquifer at the downgradient edge of the contaminated zone (m),} \\ V_{wfr} &= \text{water flow rate in the saturated zone (m/yr),} \\ I &= \text{infiltration rate (m/yr),} \\ J_x &= \text{hydraulic gradient (dimensionless),} \\ K^{(sz)}_x &= \text{saturated hydraulic conductivity of saturated zone (m/yr),} \end{aligned}$$

$l =$	length of contaminated zone parallel to the hydraulic gradient (maximum distance from upgradient edge to downgradient edge parallel to the hydraulic gradient, (m),
$d_w =$	distance of well intake below the water table (m),
$\tau_{ii} P_e^{(sz)} R_{di}^{(sz)} l / V_{wfr} =$	time for the i th principal radionuclide to be transported from the upgradient edge to the downgradient edge of the contaminated zone (yr),
$R_{di}^{(sz)} =$	retardation factor for the i th principal radionuclide in the saturated zone (dimensionless), and
$P_e^{(sz)} =$	effective porosity of aquifer (dimensionless).

Equation D.15 is used only in the ND model. The infiltration rate is given by Equation D.3.

D.3.1.3 Dilution Factor

"It is assumed that the water flow is vertically downward from the bottom of the contaminated zone to the water table; hence, no dilution will occur in the unsaturated zone. The dilution in the saturated zone is estimated using the conservative assumption that the dispersivity is zero" (Yu, 1992).

For a well located at the downgradient edge of the contaminated zone, the dilution factor is given by the following formula,

$$f_{ii} = \begin{cases} \zeta / d_w & \zeta < d_w \\ 1 & \zeta \geq d_w \end{cases} \quad (D.16)$$

where the parameters are as defined for Eq D.15.

D.3.2 Surface Water Pathway

The surface water pathway will consist of an on-site groundwater pathway segment that extends to the edge of the contaminated zone, an off-site groundwater pathway segment that extends from the edge of the

contaminated zone to a location where surface seepage occurs, and a surface water segment in which the contaminated groundwater is mixed with uncontaminated surface water. Contamination of the surface water can also occur as a consequence of erosion as contaminated soil is deposited in a nearby streambed or pond. This pathway is not included in the current version of RESRAD (Yu, 1992).

D.3.2 Breakthrough Time

The breakthrough time for the surface water pathway is assumed to be the same as that for the groundwater pathway. This relationship is illustrated in the following equation,

$$\Delta t_{i2} = \Delta t_{i1} = \Delta t_i \quad (D.17)$$

where Δt_i is calculated using Eqs E.24 through E.27 in the RESRAD manual.

D.3.2.2 Rise Time

The rise time for the surface water pathway is assumed to be the same as that used for the groundwater pathway. This relationship is illustrated in the following equation,

$$\delta t_{i2} = \delta t_{i1} \quad (D.18)$$

where δt_{i1} is given by Equation D.15.

D.3.2.3 Dilution Factor

The dilution factor for the surface water pathway is based on the assumption that the surface water is a pond and (1) the inflow and outflow for the pond are in steady-state equilibrium and (2) the annual inflow of radioactivity into the pond is equal to the annual quantity of radioactivity leached from the contaminated zone. With these assumptions, the dilution factor is the ratio of the annual volume of water that percolates through the contaminated zone to the annual total inflow of water into the pond (Yu, 1992).

Assuming that the infiltrating water flow is vertically downward, the dilution factor is given by the following formula,

$$f_{i2} = A/A_w \quad (D.19)$$

where,

A = area of contaminated zone (m^2) and

A_w = area of watershed (m^2).

APPENDIX E

CONCEPTUAL MODEL PARAMETERS

Table E.1. Effective Dose Equivalent Conversion Factors (DCF)
for External Gamma Radiation from Contaminated Ground

Radionuclide i	Surface Factors (mrem/yr)/(pCi/cm ³)	Volume Factors (mrem/yr)/(pCi/cm ³)	
		p _b =1.0 g/cm ³	p _b =1.8 g/cm ³
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	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

Source: Argonne National Laboratory, "Draft Manual For Implementing Residual
Radioactive Material Guidelines." February 1992.

Table E.2. Area Factors for External Gamma Radiation from Contaminated Ground

Contaminated Area (m ²)	Radius (m)	Area Factor FA ₁
1	0.56	0.016
25	2.8	0.4
100	5.6	0.55
500	13	0.8
1200	20	1.0

Source: Argonne National Laboratory, "Draft Manual For Implementing Residual Radioactive Material Guidelines." February 1992.

Table E.3: Depth Factors (FD_{11}) 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 (P_b) for Principal and Associated Radionuclides

Radionuclide i	$P_b = 1.0 \text{ g/cm}^3$			$P_b = 1.8 \text{ g/cm}^3$		
	T=0.15m	T=0.50m	T=1.00m	T=0.15m	T=0.50m	T=1.00m
Pu-238	9.3×10^{-1}	1.0	1.0	1.0	1.0	1.0
Pu-239	9.2×10^{-1}	1.0	1.0	1.0	1.0	1.0
Pu-240	9.2×10^{-1}	1.0	1.0	1.0	1.0	1.0
Pu-241+D	9.0×10^{-1}	1.0	1.0	9.8×10^{-1}	1.0	1.0
Pu-242	9.6×10^{-1}	1.0	1.0	1.0	1.0	1.0
Am-241	9.4×10^{-1}	1.0	1.0	1.0	1.0	1.0

Source: Argonne National Laboratory, "Draft Manual For Implementing Residual Radioactive Material Guidelines." February 1992.

Table E.4: Committed Effective Dose Equivalent Conversion Factors (DCF_{12}) for Inhalation

Radionuclide, i	Inhalation Class	DCF_{12} (mrem/pCi)
Pu-238	W	4.6×10^{-1}
	Y	3.0×10^{-1}
Pu-239	W	5.1×10^{-1}
	Y	3.3×10^{-1}
Pu-240	W	5.1×10^{-1}
	Y	3.3×10^{-1}
Pu-241+D	W	1.0×10^{-2}
	Y	5.7×10^{-3}
Pu-242	W	4.8×10^{-1}
	Y	3.1×10^{-1}
Am-241	W	5.2×10^{-1}

Source: Argonne National Laboratory, "Draft Manual For Implementing Residual Radioactive Material Guidelines." February 1992.

Table E.5: Committed Effective Dose Equivalent Conversion Factors for Ingestion

Radionuclide, i	f_i	DCF _B (mrem/pCi)
Pu-238	1×10^{-3}	3.8×10^{-3}
	1×10^{-5}	5.4×10^{-5}
Pu-239	1×10^{-3}	4.3×10^{-3}
	1×10^{-5}	5.8×10^{-5}
Pu-240	1×10^{-3}	4.3×10^{-3}
	1×10^{-5}	5.8×10^{-5}
Pu-241+D	1×10^{-3}	8.6×10^{-5}
	1×10^{-5}	9.2×10^{-7}
Pu-242	1×10^{-3}	8.6×10^{-3}
	1×10^{-5}	9.2×10^{-5}
Am-241	1×10^{-3}	4.5×10^{-3}

Source: Yu, Zielen, et al., "Draft Manual For Implementing Residual Radioactive Material Guidelines," Argonne National Laboratory, February 1992.

Table E.6: Dietary Factors (DF_{pk}) for Human Food Consumption

Primary Pathway Index, p	Ingestion Pathway	Food Class Index, k	Class Description	Dietary Factor, DF_{pk}
	Plant Foods	1	Fruits, Vegetables, and Grain	160 kg/yr
3	Plant Foods	2	Leafy Vegetables	14 kg/yr
4	Meat	1	Meat and Poultry	63 kg/yr
5	Milk	1	Milk	92 L/yr
6	Aquatic Foods	2	Fish	5.4 kg/yr
6	Aquatic Foods	2	Crustacea and Mollusks	0.9 kg/yr
7	Drinking Water	1	Drinking Water	510 L/yr

Source: Yu, Zielen, et al., "Draft Manual For Implementing Residual Radioactive Material Guidelines," Argonne National Laboratory, February 1992.

Table E.7: Vegetable/Soil Transfer Factors (B_v) for Root Uptake

Element	B_v
Pu	2.5×10^{-4}
Am	2.5×10^{-4}

Source: Yu, Zielen, et al., "Draft Manual For Implementing Residual Radioactive Material Guidelines," Argonne National Laboratory, February 1992.

Table E.8: Meat (FQR_{it}) and Milk (FQR_{is}) Transfer Factors for Root Uptake

Element	Beef, FQR_{it} , (d/kg)	Milk, FQR_{is} , (d/L)
Pu	5.0×10^{-3}	2.5×10^{-8}
Am	5.0×10^{-3}	2.5×10^{-8}

Source: Yu, Zielen, et al., "Draft Manual For Implementing Residual Radioactive Material Guidelines," Argonne National Laboratory, February 1992.

Table E.9: Aquatic Bioaccumulation Factors (FWR_{ia}) for Freshwater

Element	Fish ($k=1$), (L/kg)	Crustacea and Mollusks ($k=2$), (L/kg)
Pu	3.5	1.0×10^2
Am	2.5×10^1	1.0×10^3

Source: Yu, Zielen, et al., "Draft Manual For Implementing Residual Radioactive Material Guidelines," Argonne National Laboratory, February 1992.

VITA

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