Document Title: **Rocky Flats Plant – Occupational Environmental Dose**		Document Number: Revision: Effective Date: Type of Document: Supersedes:	ORAUT-TKBS-0011-4 02 04/23/2007 TBD Revision 01
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☐ New ☒ Total Rewrite ☐ Revision ☐ Page Change

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PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
01/06/2004	00	New technical basis document for the Rocky Flats Plant – Occupational Environmental Dose. Incorporates NIOSH and ORAU formal review comments. First approved issue. Initiated by Robert Meyer.
06/29/2004	01	Approved issue of Revision 01. NIOSH material added to Introduction; Table 4-1 columns corrected; Table 4-2 values corrected; page 50 table list change; Section B.2 ^{3}H dose factor discussion added; page 52 table ID changed. Averaged two 1973 Pu and Am intake values to provide one annual estimate; changed FEIS reference citation on page 8, and corrected reference list for 2 citations. Incorporates additional NIOSH formal review comments. Initiated by Robert Meyer.
04/23/2007	02	Approved Revision 02 initiated to update Section. 4.1.1 with standard NIOSH text, updated intakes to reflect site-wide maximum intakes which required obtaining location-specific model output as opposed to location-averaged output. Converted intake units to Bq, changed recommended AMAD to 0.3 µm for some years, clarified that resuspension was addressed in modeling. Added CDPHE data for 1999–2005, other clarifications re SC&A comments. Attachment B updated to incorporate ICRP 68 organ dose factors. Worker Outreach comments pertaining to CT-0202 and CT-0208 have been addressed in a revision of Section 4.2.3. Revised to incorporate attribution per ORAU direction. Incorporates NIOSH formal review comments and an additional comment, changing recommendation of 0.3 µm to 1.0 µm AMAD for certain years. Constitutes a total rewrite of document. This revision results in an increase in assigned dose and a PER is required. Training required: As determined by the Task Manager. Initiated by Robert Meyer.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS AND ABBREVIATIONS

AED	aerodynamic equivalent diameter
AMAD	activity median aerodynamic diameter
Bq	becquerel
CDPHE	Colorado Department of Public Health and Environment (previously Colorado Department of Health)
Ci	curie
CL	confidence limit
DOE	U.S. Department of Energy
EEOICPA	Energy Employees Occupational Illness Compensation Program Act of 2000
EPA	U.S. Environmental Protection Agency
ET	extrathoracic
fCi	femtocurie
ft	foot
FGR	Federal Guidance Report
g	gram
GEP	good engineering practice
GM	geometric mean
HEPA	high-energy particulate air
hr	hour
ICRP	International Commission on Radiological Protection
m	meter
mCi	millicurie
mi	mile
mrem	millirem
NIOSH	National Institute for Occupational Safety and Health
ORAU	Oak Ridge Associated Universities
pCi	picocurie
POC	probability of causation
RAC	Risk Assessment Corporation
RATCHET	Regional Atmospheric Transport Code for Hanford Environmental Tracking
RFETS	Rocky Flats Environmental Technology Site
RFP	Rocky Flats Plant
TBD	technical basis document
TLD	thermoluminescent dosimeter
TLLα	total long-lived alpha

U.S.C.	United States Code
wk	week
yr	year
α	alpha particle
µm	micrometer
σ	sigma
§	section or sections

4.1 INTRODUCTION

Technical basis documents and site profile documents are not official determinations made by the National Institute for Occupational Safety and Health (NIOSH) but are rather general working documents that provide historic background information and guidance to assist in the preparation of dose reconstructions at particular sites or categories of sites. They will be revised in the event additional relevant information is obtained about the affected site(s). These documents may be used to assist NIOSH staff in the completion of the individual work required for each dose reconstruction.

In this document the word "facility" is used as a general term for an area, building, or group of buildings that served a specific purpose at a site. It does not necessarily connote an "atomic weapons employer facility" or a "Department of Energy [DOE] facility" as defined in the Energy Employees Occupational Illness Compensation Program Act [EEOICPA; 42 U.S.C. § 7384l(5) and (12)]. EEOICPA defines a DOE facility as "any building, structure, or premise, including the grounds upon which such building, structure, or premise is located … in which operations are, or have been, conducted by, or on behalf of, the Department of Energy (except for buildings, structures, premises, grounds, or operations … pertaining to the Naval Nuclear Propulsion Program)" [42 U.S.C. § 7384l(12)]. Accordingly, except for the exclusion for the Naval Nuclear Propulsion Program noted above, any facility that performs or performed DOE operations of any nature whatsoever is a DOE facility encompassed by EEOICPA.

For employees of DOE or its contractors with cancer, the DOE facility definition only determines eligibility for a dose reconstruction, which is a prerequisite to a compensation decision (except for members of the Special Exposure Cohort). The compensation decision for cancer claimants is based on a section of the statute entitled "Exposure in the Performance of Duty." That provision [42 U.S.C. § 7384n(b)] says that an individual with cancer "shall be determined to have sustained that cancer in the performance of duty for purposes of the compensation program if, and only if, the cancer … was at least as likely as not related to employment at the facility [where the employee worked], as determined in accordance with the POC [probability of causation[1]] guidelines established under subsection (c) …" [42 U.S.C. § 7384n(b)]. Neither the statute nor the probability of causation guidelines (nor the dose reconstruction regulation) define "performance of duty" for DOE employees with a covered cancer or restrict the "duty" to nuclear weapons work.

As noted above, the statute includes a definition of a DOE facility that excludes "buildings, structures, premises, grounds, or operations covered by Executive Order No. 12344, dated February 1, 1982 (42 U.S.C. 7158 note), pertaining to the Naval Nuclear Propulsion Program" [42 U.S.C. § 7384l(12)]. While this definition contains an exclusion with respect to the Naval Nuclear Propulsion Program, the section of EEOICPA that deals with the compensation decision for covered employees with cancer [i.e., 42 U.S.C. § 7384n(b), entitled "Exposure in the Performance of Duty"] does not contain such an exclusion. Therefore, the statute requires NIOSH to include all occupationally derived radiation exposures at covered facilities in its dose reconstructions for employees at DOE facilities, including radiation exposures related to the Naval Nuclear Propulsion Program. As a result, all internal and external dosimetry monitoring results are considered valid for use in dose reconstruction. No efforts are made to determine the eligibility of any fraction of total measured exposure for inclusion in dose reconstruction. NIOSH, however, does not consider the following exposures to be occupationally derived:

- Radiation from naturally occurring radon present in conventional structures
- Radiation from diagnostic X-rays received in the treatment of work-related injuries

[1] The U.S. Department of Labor is ultimately responsible under the EEOICPA for determining the POC.

4.1.1 Purpose

The preparation of this report used available information about the Rocky Flats Plant (RFP) environment dating back to 1952. The user is strongly advised to consider the remarks in the text on appropriate use and interpretation of the material.

O*ccupational environmental dose* refers to the radiation dose received in the course of work duties outside Plant buildings but on the RFP site. Internal and external exposures to radionuclides in the outdoor environment are considered separately here in calculating this dose. Estimated occupational environmental dose can be utilized when a worker did not have the potential for routine exposures.

4.1.2 Scope

Section 4.2 presents information necessary to estimate internal environmental dose. It identifies the radionuclides of concern. Screening the list of radionuclides relied on work done for the Historical Public Exposure Studies on Rocky Flats (ChemRisk 1994a; Rood and Grogan 1999). Section 4.2 discusses the resulting source terms (release rates) for radionuclides considered potentially significant to internal environmental dose and provides estimated annual inhalation intake activities of radionuclides.

Section 4.3 contains information necessary for estimating external environmental dose. Ambient doses, taken from annual environmental reports for RFP published from 1975 through 1995, were developed for the site. The reports summarize external dose as measured by thermoluminescent dosimeters (TLDs) at the Plant, its general environs, and selected nearby communities.

Section 4.4 considers uncertainties in the information provided for estimating occupational environmental dose. The discussion addresses sources of uncertainty and provides quantitative information where possible.

4.2 INTERNAL DOSE FROM ONSITE ATMOSPHERIC RADIONUCLIDE CONCENTRATIONS

4.2.1 Radionuclides of Concern

The Historical Public Exposures Studies on Rocky Flats were conducted in the 1990s as part of a 1989 Agreement in Principle between DOE and the State of Colorado to identify potential health effects in nearby communities exposed to past releases. Phase I and Phase II of the studies provided comprehensive analyses of releases of radionuclides from RFP during the period from 1953 to 1989, although component assembly operations actually began in 1952 and all production operations formally ceased in 1992 (ChemRisk 1992, 1994a; Voillequé 1999a,b,c; Weber et al. 1999).

The Phase I study identified several radionuclides as potentially significant releases – ^{3}H, natural thorium, enriched and depleted uranium, $^{239/240}$Pu, ^{241}Pu, and ^{241}Am. The results of the Phase I study identified plutonium as the primary material of concern with respect to offsite exposures. The Phase II study focused the air pathway exposure assessment on the isotopes of plutonium. The potential importance of ^{3}H, enriched and depleted uranium, and ^{241}Am to onsite exposures was reevaluated here to determine if previous determinations of insignificance were relevant for occupational exposures. Releases of natural thorium were difficult to quantify, but were probably insignificant based on a review of processes and ventilation filter use (ChemRisk 1994a, Task 5, p. 123).

To evaluate the potential significance of radionuclides other than isotopes of plutonium, an estimate was developed of committed inhalation dose from a 1-yr intake using airborne stack emission estimates from the Phase I study, the air dispersion modeling results from Phase II, an assumed inhalation rate of 2,400 m^3/yr (ICRP 1975), and dose factors from International Commission on Radiological Protection (ICRP) Publication 68 (ICRP 2001). Attachment A contains a summary of the atmospheric dispersion model. Attachment B discusses the methods and results of this screening evaluation. Briefly, the maximum organ dose due to inhalation [assuming an activity median aerodynamic diameter (AMAD) of 0.3 µm) in any given year since 1953 for any of these radionuclides was estimated to be that for ^{241}Am, on the order of 34 mrem for the stack releases. The maximum predicted committed doses for ^{3}H, depleted uranium, and enriched uranium for a 1-yr intake were 0.06 mrem, 1.2 mrem, and 0.65 mrem, respectively. The Phase I study estimated that ^{241}Am is potentially present in excess of 0.23 times the alpha activity of ^{239,240}Pu in the 903 Area due to ingrowth of ^{241}Am from ^{241}Pu in the cutting oil stored in that area and in soils contaminated with the cutting oil (ChemRisk 1994b, Appendix H). Therefore, ^{241}Am associated with soil resuspended from the 903 Area or emitted with plutonium isotopes from stacks was considered a contributor to dose. Stack releases of ^{3}H and the uranium isotopes were excluded as potentially significant contributors (Attachment B).

The *Final Environmental Impact Statement for the Rocky Flats Plant* (DOE 1980) indicates an isotopic composition of plutonium by weight as follows:

Table 4-1. Isotopic composition of RFP plutonium.

Isotope	Percent by weight	Percent of Pu alpha activity[a]
Pu-238	0.01	2.33
Pu-239	93.79	79.62
Pu-240	5.80	18.04
Pu-241	0.36	(beta emitter)
Pu-242	0.03	0.00161

a. From ChemRisk (1994a, p. 105, Table 2-34).

As indicated in the table, ^{238}Pu and ^{242}Pu are minor contributors to the alpha activity of plutonium expected in the RFP environment [1]. Thus, the following sections report source terms and intakes for ^{239,240}Pu and ^{241}Am only.

4.2.2 Source Terms

The discussion of atmospheric source terms for ^{239,240}Pu and ^{241}Am released to the RFP environment addresses two periods: the operational, or pre-1993, period, when production activities were ongoing, and the post-1992 period, when production activities had ceased and releases were more likely to occur as a result of past contamination or decontamination and decommissioning activities.

4.2.2.1 Operational Period (Pre-1993) Source Terms

In 1952, the only operational activities that took place at RFP were in Building 991 (Putzier 1982), in which components manufactured at other locations were assembled (ChemRisk 1992). No significant emissions are estimated to have occurred during this year. From 1953 through part of 1992, fabrication and recycling activities at RFP resulted in radionuclide releases to the onsite atmospheric environment as a result of “routine” operations (continuous releases), and “nonroutine incidents” (discrete events). The term “routine” was used in the Radiological Assessments Corporation (RAC) Phase II dose reconstruction reports to distinguish continuous releases from the release spikes that

occurred during the 1957 and 1969 fires and during 903 Area high-wind events. However, routine releases "included discharges that were due to a variety of unplanned events and conditions that arose during facility operations," including "small fires involving plutonium metal," the "peroxide tank explosion in Building 771 in 1957 and the glovebox drain fire in Building 776 in 1965," among other events (Voillequé 1999c).

The most significant discrete release occurred during and shortly after September 11, 1957. A glovebox fire in Building 71 (now called Building 771) resulted in a release of plutonium estimated at 21 Ci (50th-percentile estimate; Voillequé 1999a). The next most significant discrete release location was the 903 Drum Storage Area (also called the 903 Pad or 903 Area). An estimated 3.1 Ci (50th percentile) of plutonium (<30-µm size fraction) were released from the 903 Pad over several years, mainly as a result of mechanical disturbance and wind action (Weber et al. 1999). This estimate consists of the 24-hr integrated release quantities for 24 identified discrete events during the 1964-to-1969 period. An asphalt pad placed over the area in 1970 decreased the source term dramatically, although resuspension of downwind contaminated soil continued to disperse plutonium to the air in later years. The third most significant nonroutine contaminant release occurred during the May 11, 1969, fire, when approximately 0.037 Ci (37 mCi) of plutonium were released from the Building 779 stack (Voillequé 1999b).

Total routine (non-discrete-event) plutonium emissions from 1953 to 1989 are estimated to be on the order of 0.12 Ci (Voillequé 1999c). This estimate does not include releases due to resuspension of contaminated soil downwind of the 903 Pad or resuspension of contaminated soil in other areas of the Plant due to deposition from the primary sources. Although the release of plutonium due to resuspension is not included in this estimate of routine emissions, it is addressed in this TBD as a contributor to exposure.

4.2.2.2 Post-Operational Period (Post-1992) Source Terms

After 1992, production operations at RFP officially ceased. However, source terms of plutonium to the environment could still exist due to contaminated soils. Air monitoring continues to be carried out by the RFP contractor and the Colorado Department of Public Health and Environment (CDPHE). Average and maximum annual median ambient concentrations have not been observed to increase since operations ceased, despite the decommissioning activities that have taken place over the last 12 yr (Table A-2, Attachment A).

4.2.3 Annual Intake of Radioactivity

To calculate intake of ^{239,240}Pu and ^{241}Am, the estimated site-wide maximum annual median [2] air concentrations of these isotopes in the RFP environment were multiplied by an annual inhalation rate. The assumed intake rate was 2,400 m^3/yr (ICRP 1975), corresponding to an hourly rate of 1.2 m^3, for light activity and a 2,000-hr work year. Intake can be scaled for increased inhalation rates or other than 2,000 hr of exposure.

Air concentrations of ^{239,240}Pu and ^{241}Am were estimated as described in Attachment A. Onsite air monitoring data are the preferred source of air concentrations (see Attachment A) for ^{239,240}Pu, but in the early years (until 1964) such data were not sufficiently descriptive or complete to allow reliable estimates. Thus, dispersion modeling results were used to estimate air concentrations of ^{239,240}Pu for these years. During these early years, stack or building vent emissions were the main source of plutonium to onsite air, and measurements of these releases are available. Resuspension of previously deposited isotopes also contributed to onsite air concentrations. The model used (described in Attachment A) addressed contributions from the primary sources identified in the

Phase I study (ChemRisk 1992, 1994a) as well as resuspension. The ratios of ^{241}Am activity to $^{239/240}$Pu activity in effluents were not measured until the 1980s; however, between 1985 and 1989, this ratio averaged 0.22 (ChemRisk 1994a). This ratio likely overestimates the fractional release in earlier years, when less ^{241}Am had grown in to the plutonium available for processing Therefore, this ratio of 0.22 is used to estimate ^{241}Am concentrations from 1953 to 1964.

After 1964, suspension or resuspension (Rood and Grogan 1999, p. 57) of contaminated soil was the main source of plutonium to onsite air. Air monitoring data provided either total long-lived alpha (TLLα) concentrations, from which ^{239,240}Pu values could be derived, or actual measurements of ^{239,240}Pu. The annual environmental reports (Dow 1972a, 1973 to 1976; Rockwell 1977 to 1989; EG&G 1989 to 1993; Kaiser-Hill 1994) were useful in providing summaries of air concentrations by sampler location based on monthly reporting through 1994. After 1994, Rocky Flats Environmental Technology Site (RFETS) monitoring reports and the CDPHE monitoring reports provided quarterly summaries of monitoring results. Activity concentrations of ^{241}Am are estimated after 1964 by assuming that the concentration of ^{241}Am is 30% of the ^{239,240}Pu concentration based on measurements of the ^{241}Am/^{239}Pu activity in RFP soil by two separate researchers in the 1970s (Poet and Martell 1972; Krey et al. 1976) and more recently by Litaor and Allen (1996). This assumption is favorable to claimants because the average measured activity ratios in soil were found to be less than 0.20 by these three groups of researchers [3].

Table 4-2 lists estimated annual intakes of ^{239,240}Pu between 1953 and 1964, based on the atmospheric modeling [4] described in Attachment A. The values are expressed in becquerels per year. The calculated intakes represent a maximum annual median (50th percentile) of the six computational nodes evaluated in the RFP industrial area for 500 Monte Carlo model realizations simulated for each year, and are exclusive of the buffer zone (Figure 4-2). The location of the maximum concentrations was the north-central, northeast, or southeast node, which is expected based on the locations of the primary sources and the general west-to-east wind direction. The median intakes in Table 4-2 correspond to isotopes associated with particles smaller than 15-µm aerodynamic equivalent diameter (AED), which is an upper limit for respirable particles according to Rood and Grogan (1999, p. iv).

Table 4-2 lists two results for 1957. Results for "1957" include the September 11 fire, which caused the annual intakes to be substantially higher than during the years before and after. If a worker was known to have been present during that year, and that individual might have been present in September, it is appropriate to use this value. The results for "1957, w/o fire" can be used for individuals who worked a partial year that did not include the month of September. Elevated releases of ^{239,240}Pu and ^{241}Am attributable to the 1957 fire occurred over several hours after the fire began at approximately 10:00 p.m. on September 11. Exposure to the direct releases would have occurred during that month (the air concentrations associated with soil-deposited ^{239,240}Pu from the fire are included in both 1957 values by considering resuspension of contaminated soil in the dispersion modeling).

Table 4-3 lists estimated annual intakes of ^{239,240}Pu and ^{241}Am between 1965 and 2002. The values for ^{239,240}Pu in this table are based on site-wide maximum annual median measured concentrations at samplers across the site, and thus represent concentrations at the locations of higher concentration (typically near the 903 Area). Therefore, these values are inherently favorable to claimants when applied as an estimate of environmental exposure for the industrial area. The ^{239,240}Pu air concentrations supporting the intakes in Table 4-3 are described in Attachment A and summarized in Table A-2. Intakes were calculated from air concentrations by assuming a respirable fraction of 1.0, despite the reported values of this parameter ranging from 0.2 to 0.4 in a review of the subject in Rope et al. (1999, pp. III-79 to III-81). Low- and high-volume air samplers at RFP collected particles

Table 4-2. Site-wide maximum annual median inhalation intakes of ^{239,240}Pu and ^{241}Am for 1953 to 1964, based on atmospheric modeling (AED <15 µm; assume respirable).[a]

Year	Pu-239, 240 intake (Bq/yr)	Am-241 intake (Bq/yr)[b]
1953	3.6E-05	7.8E-06
1954	1.7E-04	3.7E-05
1955	1.7E-04	3.6E-05
1956	5.5E-04	1.2E-04
1957	6.8E-02	1.5E-02
1957 w/o fire	2.1E-02	4.7E-03
1958	9.1E-03	2.0E-03
1959	8.1E-03	1.8E-03
1960	5.0E-03	1.1E-03
1961	2.9E-03	6.4E-04
1962	5.4E-03	1.2E-03
1963	1.4E-02	3.0E-03
1964	6.1E-02	1.3E-02

a. Atmospheric modeling described in Attachment A [4].
b. Am-241 intake is assumed to be 22% of the Pu-239/240 intake (Section 4.2.3).

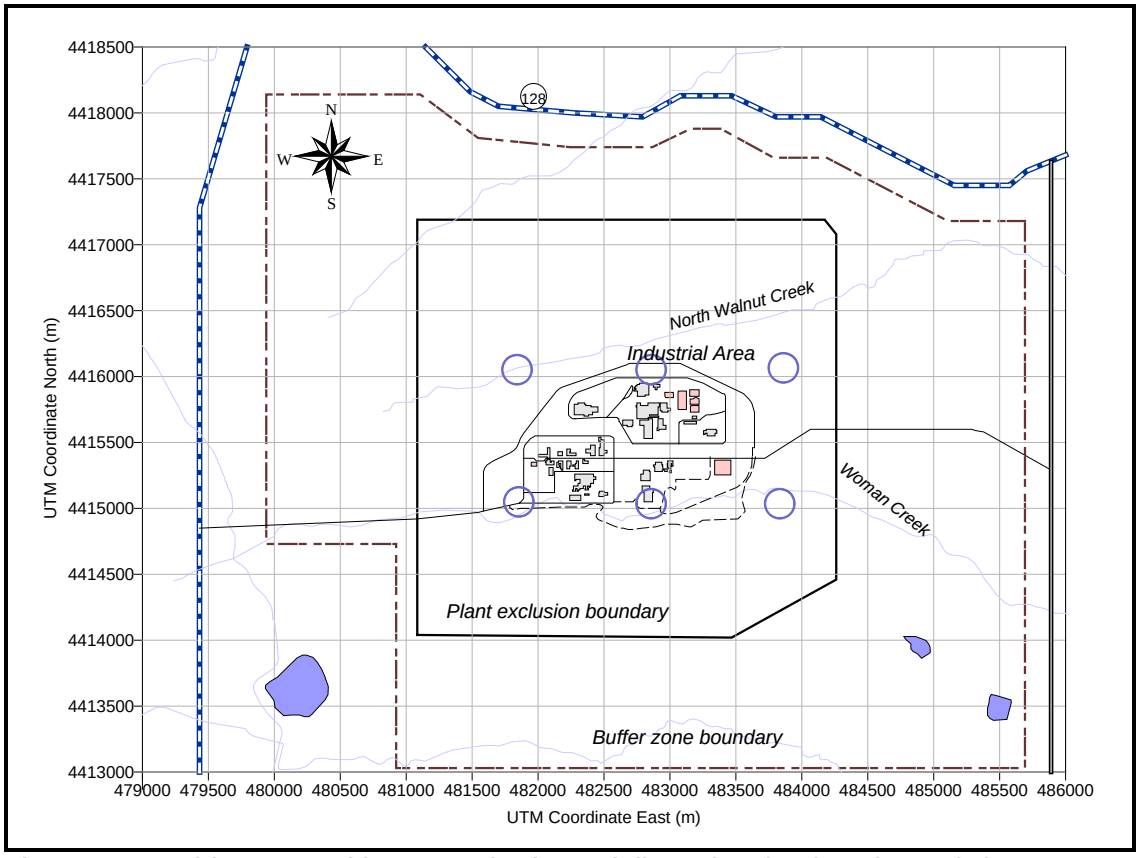

Figure 4-1. Grid map used in atmospheric modeling, showing locations of six computational nodes representing the RFP Industrial Area [4].

Table 4-3. Site-wide maximum annual median inhalation intake of ^{239,240}Pu and ^{241}Am (1965 to 2005), based on monitoring data (respirable fraction of sampled particles = 1.0).

Year	Pu-239, 240 intake (Bq/yr)[a]	Am-241 intake (Bq/yr)[b]
1965	1.8E-01	5.5E-02
1966	3.3E-01	9.8E-02
1967	1.1E+00	3.3E-01
1968	3.4E+00	1.0E+00
1969	5.9E+00	1.8E+00
1970	2.9E-01	8.6E-02
1971	3.3E-01	1.0E-01
1972	3.4E-01	1.0E-01
1973	4.7E-01	1.4E-01
1974	2.8E-01	8.4E-02
1975	8.6E-02	2.6E-02
1976	1.2E-01	3.6E-02
1977	5.3E-02	1.6E-02
1978	7.6E-02	2.3E-02
1979	4.4E-02	1.3E-02
1980	4.0E-02	1.2E-02
1981	4.9E-02	1.5E-02
1982	4.2E-02	1.3E-02
1983	3.8E-02	1.1E-02
1984	4.9E-02	1.5E-02
1985	3.6E-02	1.1E-02
1986	4.1E-02	1.2E-02
1987	1.1E-01	3.3E-02
1988	6.3E-02	1.9E-02
1989	4.4E-02	1.3E-02
1990	8.4E-02	2.5E-02
1991	1.0E-01	3.1E-02
1992	5.1E-02	1.5E-02
1993	3.1E-02	9.4E-03
1994	3.6E-02	1.1E-02
1995	2.0E-02	5.9E-03
1996	7.3E-03	2.2E-03
1997	5.9E-03	1.8E-03
1998	1.1E-02	3.2E-03
1999	1.2E-02	3.5E-03
2000	1.3E-02	3.9E-03
2001	1.4E-02	4.2E-03
2002	4.5E-03	1.3E-03
2003	1.6E-02	4.8E-03
2004	2.4E-03	7.1E-04
2005	9.1E-03	2.7E-03

a. Calculated from air concentration data in Table A-2.
b. Calculated by multiplying ^{239,240}Pu intake by 0.30 (see Section 4.2.3).

larger than respirable (Rope et al. 1999) to varying degrees as samplers were replaced over the years. Because the respirable fraction of sampled particles is not accurately known, a respirable fraction of 1.0, which is favorable to claimants, was assumed.

The values reported for ^{241}Am in Table 4-3 (after 1970) were calculated by multiplying the ^{239,240}Pu intake values by 0.30, in accordance with the rationale described above in this section. Again, a respirable fraction of 1.0, which is favorable to claimants, was assumed.

Annual intakes estimated in Tables 4-2 and 4-3 are based on a 2,400-m^3/yr inhalation rate, but can be scaled to a different rate. Furthermore, the values can be scaled for partial-year exposures, with the following cautionary note. For 1957, approximately 70% of the intake of ^{239,240}Pu can be attributed to the September 11 fire. Thus, if a worker was present on the site for only a portion of 1957, but during September, the entire annual intake should be assumed. If a worker was present on the site in 1957, but not during September, the intake designated “1957 w/o fire” should be assumed, and scaling of this value for a partial-year exposure can be done.

The assumed solubility of inhaled ^{239,240}Pu should consider the following information. Plutonium in metal-working operations and involved in fires is generally insoluble (type S or slowly transportable in the lungs), but can be highly insoluble (super type S). Exceptions, such as plutonium metal associated with solvents, might exist. Plutonium in chemical processing operations can be either soluble (type M or moderately transportable in the lungs) or insoluble. The solubility of plutonium should be selected based on what is most favorable to the claimant in light of the organ of interest [5].

The AMAD of airborne ^{239,240}Pu and ^{241}Am will vary according to the source and, thus, according to location on the Plant site. For routine releases from stacks and vents in which high-energy particulate

air (HEPA) filters are operating as designed, the particle size of stack-effluent particles has been reported to be on the order of 0.3 µm AMAD (Rood 1999; Grogan, Sinclair, and Voillequé 2000). The AMAD of particles released from the two larger fires (1957 and 1969) were not assessed, but there was evidence that the HEPA filtration systems did not remain intact throughout these events (Voillequé 1999a,b). A study of aerosols generated from another RFP fire involving plutonium and solvents indicated an mass median diameter on the order of 0.32 µm for this incident (Mann and Kirchner 1967), which correlates to an AMAD of approximately 1-µm, using the correlation provided by Hayden (1976) for RFP environmental plutonium and stack effluent air. However, the site-wide maximum intakes listed in Table 4-3 often reflect the air concentrations at the eastern edge of the site that resulted from suspension and resuspension of soil contaminated with ^{239,240}Pu and ^{241}Am from the 903 Area. The AMAD of airborne particles containing plutonium in this area of RFP has been characterized as ranging from 2 to 7 µm (Grogan, Sinclair, and Voillequé 2000). Although the physical diameters of plutonium particles in soil were found to be on the order of 0.3- to 1-µm AMAD, it appears that the airborne plutonium particles in this area were attached to soil particles, resulting in an aerosol most appropriately characterized by an AMAD of ~5 µm (Grogan, Sinclair, and Voillequé 2000).

Thus, the AMAD is a time-dependent as well as location-dependent attribute of airborne radionuclides at RFP. Unfortunately, the relative contributions of the various sources of airborne plutonium at specific outdoor work locations are not known. From Figure 2-5 and Table 2-D in ORAUT (2006a), it is clear that most of the work locations at RFP were upwind of the 903 Area plutonium source because the predominant wind direction at RFP is from the northwest (Rockwell 1989). Measurements of soil concentrations of plutonium in 1988 surrounding RFP, at distances of 1 and 2 mi from the center of the Plant, indicated dramatically larger concentrations east and southeast of the 903 Area than in other areas (Rockwell 1989). However, the degree to which the concentrations upwind of the 903 Area were influenced by resuspended plutonium is not known. Outdoor workers in the vicinity of the buildings from which routine releases occurred, and upwind of the 903 Area, could have been exposed to particulates with AMADs on the order of 0.3 µm, although resuspended particles would also be present at their location. The following recommendations are made based on the information given above. For intakes estimated prior to 1965 (Table 4-2), an AMAD of 1.0 µm should be assumed for airborne ambient ^{239,240}Pu and ^{241}Am, because worker intakes largely resulted from routine releases, the 1957 fire, and any resuspension of deposited ^{239,240}Pu and ^{241}Am that occurred in the worker's vicinity . An AMAD of 1.0 µm should also be assumed for intakes occurring during 1965, 1966, and 1970 to 1993 [6]. The disturbance of the 903 Area as part of an attempt to remove leaking barrels, and subsequent high-wind events that served as the main dispersal mechanism for plutonium contaminating the soils of the 903 Area, occurred between 1967 and 1969. During 1967, 1968, and 1969, and after 1993, an AMAD of 5 µm should be assumed [7]. The site-wide maximum intakes from 1967 to 1969 (Table 4-3) are clearly dominated by the suspended plutonium that originated from the 903 Area before placement of the asphalt pad. After 1993, when production had ceased, resuspension of plutonium is the mostly likely source of airborne plutonium.

The recommendation to assume an AMAD of 1.0 µm from 1970 through 1993 is based on the fact that air concentrations downwind of the 903 Area, which are better characterized by an AMAD of 5.0 µm, tended to be only slightly (less than an order of magnitude) higher than other onsite areas, but not always. In 1972, the onsite airborne concentrations downwind of the 903 Area were 2 to 3 times higher than in other areas of RFP (Dow 1972b). However, in 1990 to 1992, the air concentrations in the main production areas of RFP (northern section of the industrial zone) exceeded those downwind of the 903 Area.

These assumptions are favorable to the claimant in the following respects: (1) for most organs, assuming an AMAD of 1.0 µm increases the dose by about a factor of 1.5 over the dose calculated by

assuming an AMAD of 5.0 µm; and (2) using the site-wide maximum intakes often implicitly assumes the worker is exposed to the air concentrations downwind of the 903 Area, which is not the location of most exposures. The ET airways dose factor is a factor of 1.5 times higher for the AMAD assumption of 5 µm (the particle size more appropriate for resuspended plutonium) versus 1.0 µm (1.5×10^{-5} Sv/Bq versus 9.5×10^{-6} Sv/Bq), and thus for cases in which that organ dose is of most interest, the AMAD of 5.0 µm should be assumed for all years.

4.3 EXTERNAL EXPOSURE TO ONSITE ATMOSPHERIC RADIONUCLIDE CONCENTRATIONS

4.3.1 Radionuclides of Concern

As described in Section 4.2.1, ^{3}H, natural thorium, enriched and depleted uranium, $^{239/240}$Pu, ^{241}Pu, and ^{241}Am were identified as having been released to the air during the RFP operational period. However, because none of the isotopes of concern is a strong gamma emitter, there is little external dose.

4.3.2 Exposure Rates

Prior to 1975, external exposure of workers was determined by the use of film badges, not TLDs (see ORAUT 2006b, Section 6.2). Film badges are not well suited to environmental monitoring, and environmental measurements prior to 1975 are not readily available. The determination concerning this lack of data is consistent with other site evaluations. Rope et al. (1999) pointed out that before the early 1970s, environmental data were fewer and of lower quality than later data. In his review of RFP (covering 1952 to 1982), Putzier (1982) spent little time discussing external occupational exposure measurements and none describing outdoor measurements. This is largely because the concern regarding environmental exposures to workers or the public was centered on plutonium. Rope et al. (1999) described external gamma exposures, but the information is limited to an analysis of aerial survey data that target plutonium by measuring ^{241}Am.

Data that can be used to estimate external environmental dose exist in annual environmental reports for 1975 to 1994 (Dow 1972a, 1973 to 1976; Rockwell 1977 to 1989; EG&G 1989 to 1993; Kaiser-Hill 1994). Gamma exposure rates were routinely measured at 12 to 15 locations on the site. Those data are plotted in Figure 4-2 for continuous exposures during a year (8,760 hr) and summarized in Table 4-4 for 2,500 hr/yr exposures. The locations of the monitoring stations were not available; however, a site-wide maximum value is estimated by adding the recommended standard deviation (described below), reflecting both spatial and temporal variation, to the site-wide mean value [8].

For the 19-yr period from 1975 to 1993, the number of independent measurements ranged from 87 to 176 per year. Table 4-4 lists the reported means and standard deviations (2σ) of the measured samples for these years with the exception of 1977. For 1977, only the mean was reported. There is no explanation available for the relatively large standard deviations in 1975, 1976, and 1978. Due to this large variation in reported standard deviations, a recommended standard deviation value (1σ) was developed based on the largest reported standard deviation. The recommended standard deviation in Table 4-4 is based on the 1975 value, which is calculated to be 18% of the mean. This recommendation is favorable to claimants because it results in higher calculated maximum dose rates [9].

There is no significant trend to the means and maximums plotted in Figure 4-2. As mentioned above, effluents from RFP were largely alpha-emitting radionuclides with no substantial gamma component with the exception of ^{241}Am. Releases attributable to incidents that might have vented outside

buildings, or due to suspension or resuspension of contaminated soil, would not tend to increase the gamma exposure rate appreciably due to the relatively large contribution of naturally occurring radioactivity to exposure rates measured. Workers subject to environmental doses from such incidents would be affected to a far greater extent by internally deposited radionuclides.

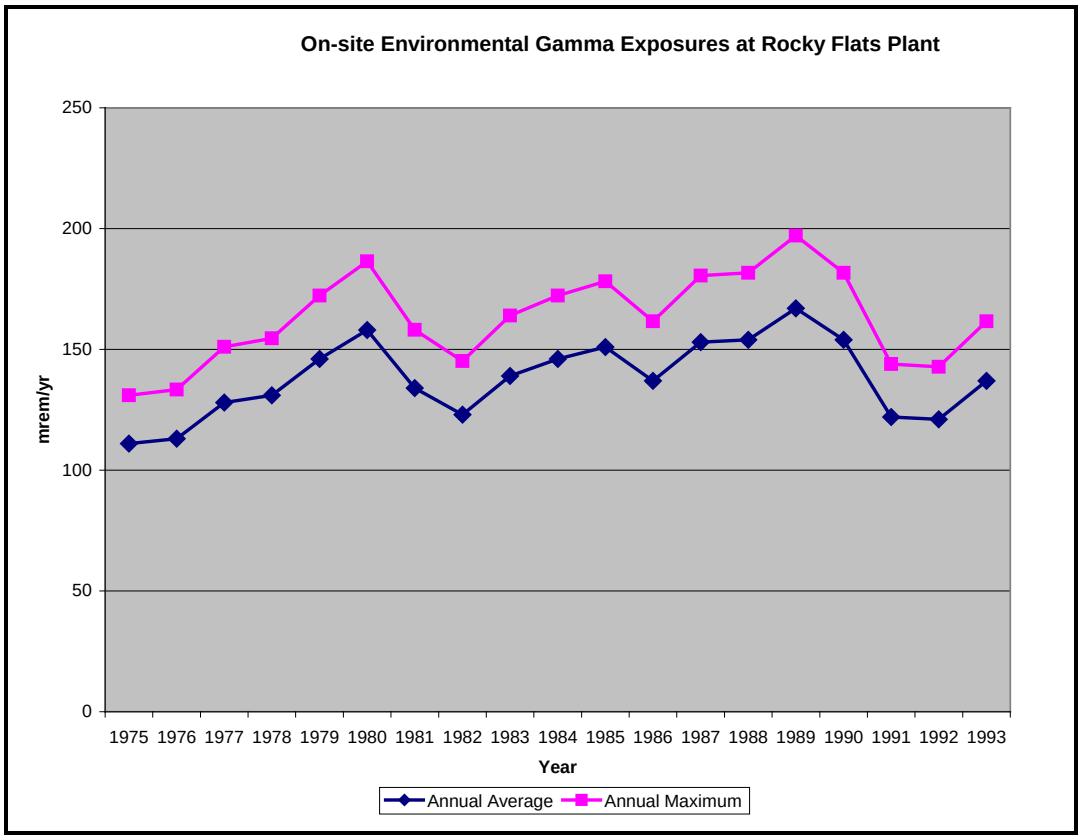

Figure 4-2. External dose (mrem/yr) at RFP as a function of year.

Therefore, it is reasonable to assign the average value of 39 ±7 mrem/yr (2,500 hr) to years not represented on this table. This value represents the average of means corresponding to the 19 yr for which measurements were reported. The assumed standard deviation associated with this average value is based on the assumed 18% standard deviation. This dose rate represents the total dose, including background, so use of these values in estimating individual worker doses is favorable to the claimant.

The listed dose rates in Table 4-4 apply to a best-estimate work year exposure of 2,500 hr, as defined in ORAUT-PROC-0060 (ORAUT 2006c).

Ambient onsite gamma is significantly larger ($p < 0.05$) than ambient gamma measured at "perimeter" stations, but only by an average of 9% for years for which data were reported (Dow 1972a, 1973 to 1976; Rockwell 1977 to 1989; EG&G 1989 to 1993; Kaiser-Hill 1994). This would seem to indicate that about 3 mrem/yr (for a 2,500-hr/yr exposure) could be contributed by contamination inside the exclusion zone boundary for these years. Thus, increases in airborne contamination will not necessarily indicate significant increases in total external dose. However, between 1965 and 1970, the large increase in inhalation intake of plutonium is due to soil contamination of the 903 Area before paving of that area. It is likely that the external dose rate at that location might have been elevated compared to other locations at the site due to the ^{241}Am present. Unfortunately, soil concentrations in

the barrel storage location are not available, and few soil concentration data are available for the site prior to 1969 (Rood and Grogan 1999). In an attempt to estimate external dose to an onsite worker from contaminated soils in the vicinity of the 903 storage area, a plutonium soil contamination value of 26 µCi/m^2 (9.6 × 10^5 Bq/m^2) is assumed, based on the 1973 site environmental report, which reports this value as the maximum observed in 1970 just downwind of the 903 Pad. Using Federal Guidance

Table 4-4. External gamma radiation (mrem/yr).[a] Blank indicates no data available.

Year	Number of measurements	Reported mean dose rate	Reported standard deviations (2σ)	Recommended standard deviation (σ)	Maximum dose rate[b,c]
1953–1964		39[c]		7	46
1965–1970		39[c]		17	56[d]
1971–1974		39[c]		7	46
1975	87	32	11	6	38
1976	134	32	10	6	38
1977	98	37	9	7	44
1978	126	37	10	7	44
1979	133	42	3	7	49
1980	131	45	2	8	53
1981	125	38	2	7	45
1982	120	35	1	6	41
1983	135	40	1	7	47
1984	142	42	2	7	49
1985	93	43	2	8	51
1986	147	39	1	7	46
1987	100	44	1	8	52
1988	109	44	2	8	52
1989	132	48	1	9	57
1990	143	44	1	8	52
1991	108	35	1	6	41
1992	176	35	1	6	41
1993	176	39	1	7	46
After 1993		39[c]		7	46
Mean 1975–1993		39[c]		7	
2 S.D. (2σ)		7			

a. Dose rate corresponding to an exposure time of 2,500 hr/yr.
b. Calculated by adding the recommended standard deviation to the mean dose rate, which is 18% of the mean.
c. Average of means reported for 1975 through 1993.
d. Maximum reflects calculated contribution from americium in barrel storage area prior to placement of asphalt pad.

Report (FGR) No. 12 (Eckerman and Ryman 1993) dose conversion factors for surface-contaminated soils, assuming that the maximum observed concentration was constant over the entire site, and using the mean isotopic ratio reported by Krey et al. (1976) for ^{241}Am/^{239}Pu in RFP soil of 0.13, doses can be calculated at 1 m above ground surface of approximately 3 mrem/yr (for 2,500-hr/yr exposure).

Another approach taken to estimate the soil concentration in the barrel storage area before paving was based on estimates of the total ^{239}Pu released. According to Weber et al. (1999), the highest release estimate for ^{239}Pu in the 903 storage area was on the order of 1,000 g, which corresponds to 62 Ci. If one assumes that this is spread over the 550- by 475-ft contamination zone of the 903 Area originally described (Weber et al. 1999), a maximum estimate of external dose of 17 mrem/yr for ^{241}Am is obtained [assuming Krey et al. (1976) mean isotopic ratio of 13% for ^{241}Am:^{239}Pu, the appropriate FGR 12 dose conversion factor, a depth of contamination of 15 cm, and 2,500-hr/yr exposure].

Finally, this TBD analysis attempted to ascertain what other sources of external exposure might be present. Using dose factors in FGR No. 12 (Eckerman and Ryman 1993), the analysis calculated external dose from submersion in air containing ^{241}Am. The ^{241}Am levels were calculated using isotopic ratios published by Krey et al. (1976) and modified by RAC when developing soil action levels for RFETS. Doses from ^{241}Am in that scenario were negligible, less than 1 µrem/yr.

The results of these considerations suggest that use of the ambient gamma values for external environmental dose is reasonable for unmonitored workers throughout the period from 1953 to the present, with the possible exception of the period after plutonium began leaking from the barrel storage area and before placement of the asphalt pad in that area. The maximum estimated increment to the measured ambient gamma levels was calculated to be 17 mrem/yr for a 2,500-hr/yr exposure. Thus, this quantity is added to the measured mean gamma level (39 mrem/yr) applied for 1965 to 1970, with the resulting value of 56 mrem/yr listed in Table 4-4 as the site-wide maximum.

4.4 UNCERTAINTY

Uncertainties in estimates of plutonium intake and external dose to an individual employed at RFP are associated with natural variations in environmental concentrations, lack of precise information about locations and durations of exposures, and limitations of monitoring data. Not all of these uncertainties can be quantified.

4.4.1 Uncertainty in Internal Exposure Estimates

4.4.1.1 Intakes Estimated for 1953 to 1964

The following discussion on uncertainties in the atmospheric dispersion model predictions used to estimate intakes for the period from 1953 to 1964 interprets the pertinent text from a Phase II document by Rood and Grogan (1999). Uncertainties in model calculations of integrated air concentration and intake (Section 4.2.3) arise from model and parameter uncertainty. Model uncertainty arises from the inability of the computational algorithms to describe rigorously and precisely physical processes that govern the behavior of the system, due either to insufficient knowledge of the processes or inability to measure isolated mechanisms driving the processes. Model uncertainty is often evaluated in a process called “model validation,” which compares model predictions to measured parameters that have not been used to calibrate the model.

Parameter uncertainty arises because of lack of knowledge about, or inability to measure accurately, a parameter’s true value. A parameter uncertainty analysis requires the specification of probability distributions describing the value of a parameter considered to be uncertain. The assigned distribution of a parameter characterizes the degree of belief that the true but unknown value lies within a specified range of values.

The Phase II modeling effort performed parameter uncertainty analysis and model validation. Input distributions characterizing the source term, fate and transport calculations, and risk coefficients were developed for the model.

The Phase II dispersion modeling for the identified continuous and discrete sources of plutonium to the air at RFP used Monte Carlo simulations combined with simple random sampling to propagate uncertainty through the model. In simple random sampling, a random value is taken from the distribution specified for each uncertain model parameter and a single estimate of the desired endpoint is calculated. This process is repeated for a specific number of model realizations. The result is an empirical approximation of the probability distribution of the model output.

In the current application of the Phase II dispersion model, model output (in curies per year of annual intake and converted to becquerels per year of intake for Table 4-2) was developed from 500 model realizations each year and categorized into a percentile ranking. The ordered statistics for the 5th and 95th percentiles for 500 model realizations are 25 and 475, respectively. That is, if the output values for 500 realizations are sorted in ascending order, the 5th percentile represents the 25th highest value and the 95th percentile represents the 475th highest value. The distribution associated with the percentiles is not readily described as either normal or lognormal.

The components of uncertainty reflected in the annual intake estimates reflect uncertainty only in the source terms and environmental transport. Such components of uncertainty are real in the sense they can be derived from measured quantities or inferred from historical records. Uncertainty related to exposure scenarios (i.e., location and duration of exposure) were not included in the calculated statistics.

4.4.1.2 Intakes Estimated for 1965 to Present

Uncertainties associated with the reported average annual ^{239,240}Pu air concentrations for the site are provided for 1972 to 1976 and 1989 to 1994 in the annual environmental reports (Dow 1972a, 1973 to 1976; Rockwell 1977 to 1989; EG&G 1989 to 1993; Kaiser-Hill 1994). For these years, error terms representing two standard deviations about the mean (at the 95% confidence level) are calculated assuming the measurements were normally distributed. In 1977 and 1978, no error terms are reported because "they can be misleading and (their use) is considered inappropriate for the data in this report" (Rockwell 1978, 1979). These two reports state that the sampling methods would result in "nonrandom variations in the measured concentrations," and the "distribution … would not be normal." From 1979 to 1988, error terms are reported, but only by sampler location and not normalized to the site average. The error terms, when reported, are based on counting error alone, and thus represent the minimum error that can be associated with the measurements. Although counting error does contribute to data uncertainty, the uncertainty associated with a given average value for the site will also be a function of variability in environmental conditions as well as a function of both time and location. Thus, the reported confidence limits (CLs) are not useful in estimating uncertainty associated with a site average because they would undoubtedly underestimate that uncertainty.

4.4.2 Uncertainties in External Dose Estimate

Unquantifiable uncertainty in external exposures results from the lack of readily available data before 1975 or after 1993. However, onsite measurements made during that 19-yr period indicate no significant upward trend to indicate that Plant operations are increasing background. Published data for environmental external measurements have normal statistics associated with them. The data published in Table 4-4 vary considerably in the expression of uncertainty presented in the annual environmental reports. For years before 1977, no uncertainty data are available. For other years, the uncertainty varies from as much as 18% (1σ) for 1975 to less than 2% for 1983. This TBD recommends using the maximum uncertainty available in the literature, 18%, which is represented by 1981 data. The annual recommended values of uncertainty, expressed in terms of 1σ, are listed in the fifth column of Table 4-4.

4.5 ATTRIBUTIONS AND ANNOTATIONS

Where appropriate in this TBD, bracketed callouts have been inserted to indicate information, conclusions, and recommendations provided to assist in the process of worker dose reconstruction. These callouts are listed here in the Attributions and Annotations section with information provided to identify the source and justification for each associated item. Conventional references are provided in

the next section, linking data, quotations, and other information to documents available for review on the NIOSH Project computer network.

[1] McDowell-Boyer, Laura M. Oak Ridge Associated Universities (ORAU) Team. Environmental Engineer. July 2006.
The recommendation to ignore contributions of ^{238}Pu and ^{241}Pu is based on the facts that (1) their total alpha activity contributions are less than 5% of those of ^{239}Pu and ^{240}Pu, based on the reported isotopic composition of plutonium at RFP, and (2) the maximum inhalation organ dose factors for ^{238}Pu and ^{241}Pu are equal to or less than those for ^{239}Pu and ^{240}Pu. Thus, ^{238}Pu and ^{241}Pu will not contribute more than a few percent of the dose from plutonium.

[2] ORAUT-PROC-0031, DOE Technical Basis Document Development, Review, and Approval Process (ORAUT 2006d).
This procedure provides guidance in TBD preparation, and specifies that maximum site-wide annual median intakes via inhalation will be provided.

[3] McDowell-Boyer, Laura M. ORAU Team. Environmental Engineer. July 2006.
The measurements by Poet and Martell (1972) indicated that the mean activity ratio in soil ranged from 0.03 to 0.17, but the authors acknowledged that low recovery yields associated with their laboratory procedures resulted in large errors for their ^{241}Am results. Krey et al. (1976) measured the ^{241}Am/^{239}Pu ratios in soil, and found a range from 0.10 to 0.20, with a mean of 0.13, and standard deviation of 0.03. Both authors acknowledged that the ratio would increase over time and peak 70 to 80 yr after plutonium purification (around 2030). Assuming the initial isotopic composition of plutonium from Section 4.2.1, with ^{241}Pu at 0.36%, the resulting peak ratio would be about 0.18 (Poet and Martell claimed this peak was 0.54, but had assumed an isotopic ratio of 1% for ^{241}Pu, which is almost 3 times too high). In 1996, Litaor and Allen (1996) found an average onsite ratio of 0.19, although indicated difficulties related to high analytical errors with ^{241}Am. Therefore, due to uncertainty in the relative movement of the two isotopes in soil, a higher value of 0.30 is recommended.

[4] Rood, Arthur S. K-Spar Inc. Scientific Consulting. President. July 2006.
The puff trajectory model, RATCHET (Regional Atmospheric Transport Code for Hanford Environmental Tracking), was adapted by Mr. Rood from its use for the Phase II Historical Public Exposures Studies for RFP for use in estimating onsite inhalation intakes from 1953 to 1964. The model and adaptations are described in Attachment A, Section A.2.

[5] McDowell-Boyer, Laura M. ORAU Team. Environmental Engineer. July 2006.
Due to variations in the original source of particles (fires, cutting oil, etc.) and environmental factors, it is recommended that the dose reconstructor always make a selection of dose factor that is favorable to claimants with regard to plutonium solubility.

[6] McDowell-Boyer, Laura M. ORAU Team. Environmental Engineer. January 2007.
The recommendation to assume the default ICRP Publication 66 AMAD of 1.0 µm, "recommended for exposure in the general environment" during certain periods results in using inhalation organ dose factors that are higher than those for larger respirable particles (those on the order of 5 µm). The cited literature indicates that intakes from plutonium released routinely or from fires during the 1953-to-1966 and 1970-to-1993 periods are possibly smaller than the 5- µm ICRP Publication 66 default recommended for "occupational exposure settings" due in part to the presence of HEPA filter banks at the emission points.

[7] McDowell-Boyer, Laura M. ORAU Team. Environmental Engineer. July 2006.
Plutonium-contaminated particles suspended or resuspended from soil and other surfaces are known to contribute a significant portion of the airborne activity of plutonium in certain areas of the RFP site, and many of these particles are better characterized by an AMAD of 5 µm. From 1967 to 1969, a number of high-wind events occurred during and after removal of leaking barrels containing plutonium-contaminated cutting oil in the 903 Area, which resulted in dispersal of significant quantities of contaminated soil particulates, mainly in the easterly to southeasterly direction from the 903 Area. The site-wide maximum air concentrations and, thus, estimated intakes are associated with this region of RFP. The airborne plutonium in this region is best characterized by an AMAD of 5 µm. After 1993, production had ceased, and thus it is reasonable to expect that the main source of airborne plutonium would be resuspension from soil or surfaces, and HEPA-mediated emissions would no longer have occurred.

[8] ORAUT-PROC-0031, DOE Technical Basis Document Development, Review, and Approval Process (ORAUT 2006d).
This procedure provides guidance in TBD preparation and specifies that a site average value be provided along with the standard deviation and a maximum onsite dose rate (derived by adding the standard deviation to the average).

[9] Little, Craig A. ORAU Team. Radioecologist/Health Physicist. 2006
The average of the reported standard deviations (2σ) without the 1975-to-1978 values is approximately 5. The recommended value of 1σ is approximately 10 times higher than most reported values due to the uncertainty posed by the unexplained larger variabilities seen in 1975, 1976, and 1978. This is an upper bound on the uncertainty and, thus, the resulting estimates of the maximum dose rate are favorable to claimants.

[10] McDowell-Boyer, Laura M. ORAU Team. Environmental Engineer. July 2006.
Rope et al. (1999, pp. III-43 and III-44) did an extensive review of environmental data available for the RFP site and based this least-squares, best-fit estimate of the plutonium contribution to TLLα on data collected by the Health and Safety Laboratory and Dow, making standard temperature and pressure corrections as necessary. The results were very close to an estimate made by another researcher, who did not do a best-fit analysis, but rather assumed a value between 33% and 50% based on a log-log plot of data collected by the Colorado Department of Health. The Rope et al. value appears to carry more scientific weight, yet is not in conflict with the other results. Therefore, the value of 0.36 is considered the best estimate available for the period of interest.

[11] McDowell-Boyer, Laura M. ORAU Team. Environmental Engineer. July 2006.
An electronic presentation addressing special monitoring during decommissioning and demolition projects at RFETS (www.rfets.gov/eddie/Download/Main.asp?RID=163) indicates that impacts from various demolition projects undertaken in 1999 (Building 779 glovebox strip-out, Building 729 stack removal, Building 788 demolition, Building 729 demolition, Building 729 clarifier tank removal) were not significant in terms of measured isotopic air concentrations.

[12] Rood, Arthur S. K-Spar Inc. Scientific Consulting. President. July 2006.
Mr. Rood developed the RATCHET application for the Phase II Historical Public Exposure Studies project, and made modifications to the model for this study, utilizing the same source terms identified in the earlier work.

[13] Rood, Arthur S. K-Spar Inc. Scientific Consulting. President. July 2006.
The Building 776 stack conforms to the U. S. Environmental Protection Agency (EPA) definition of good engineering practice (GEP) design. According to the EPA 1995 Building Profile Input Program, building wake effects extend out to 5 times the lesser of the building height or the building perimeter width, such that Building 771 is the only building within the sphere of influence of the 776 stack. The 776 stack must be at least 29 m high (since the Building 771 height is 11.6 m) to conform to GEP and, thus, to be free of the effects of building wakes. Since the 776 stack is 44 m high, building wake effects are not a concern.

[14] Rood, Arthur S. K-Spar Inc. Scientific Consulting. President. July 2006.
The other elevated sources modeled were the Building 776 roof vents. Because some of the roof vents were an inverted "J" type, effluent was directed down toward the roof, thereby distributing the source across the roof surface. To account for this, Building 776 was modeled not as a point source but as an elevated area source, and initial dispersion coefficients were assigned. The coefficients implicitly account for the effects of building wakes by driving the plume initially down to the ground surface.

[15] McDowell-Boyer, Laura M. ORAU Team. Environmental Engineer. July 2006.
See Attribution note [10].

[16] McDowell-Boyer, Laura M. ORAU Team. Environmental Engineer. July 2006.
There is no evidence that background radioactivity in the Denver area would be significantly different from that in the RFP area; therefore, this assumption is reasonable.

[17] McDowell-Boyer, Laura M. ORAU Team. Environmental Engineer. July 2006.
Radionuclides other than $^{239/241}$Pu and ^{241}Am that have been released from RFP and contribute less than 1-mrem/yr dose to any organ in the year of maximum release are not expected to contribute more than 5% of the total environmental dose when compared to the maximum dose contributions of $^{239/240}$Pu and ^{241}Am in the same year. This was verified by comparing the maximum estimated doses for these other radionuclides (Attachment B, Tables B-1 to B-3) and the site-wide maximum doses associated with the $^{239/240}$Pu and ^{241}Am inhalation intake values in Tables 4-2 and 4-3.

[18] McDowell-Boyer, Laura M. ORAU Team. Environmental Engineer. July 2006.
This statement is supported by the text following it, which demonstrates considerable effort by ChemRisk to review effluent monitoring data, including raw data when necessary. It is important to recognize that ChemRisk reevaluated the uncertainty associated with the data reviewed, and proposed larger uncertainties due to possible measurement and recording errors.

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GLOSSARY

alpha emitters
Unstable isotopes which decay by emitting alpha particles. See *alpha particle*.

alpha particle
Positively charged particles of discrete energies emitted by certain radioactive materials; alpha particles usually expend their energy in short distances and will not usually penetrate the outer layer of skin; they are a significant hazard only when taken into the body where their energy is absorbed by tissues.

becquerel
A special unit of radioactivity. One becquerel equals 1 disintegration per second.

beta radiation
Radiation consisting of charged particles of very small mass (i.e., the electron) emitted spontaneously from the nuclei of certain radioactive elements. Most (if not all) of the direct fission products emit beta radiation. Physically, the beta particle is identical to an electron moving at high velocity.

curie
A special unit of radioactivity. One curie equals 3.7×10^{10} nuclear transitions per second.

depleted uranium
Uranium that is a byproduct of uranium enrichment, containing a lower than natural isotopic abundance of ^{235}U.

dosimeter
A device used to measure the quantity of radiation received. A holder with radiation-absorbing elements (filters) and an insert with radiation-sensitive elements packaged to provide a record of absorbed dose or dose equivalent received by an individual. See *thermoluminescent dosimeter*.

dosimetry
The science of assessing absorbed dose, dose equivalent, effective dose equivalent, etc., from external or internal sources of radiation.

enriched uranium
Uranium enhanced from its natural state to contain a higher percentage of the isotope ^{235}U.

exposure
As used in the technical sense, exposure refers to a measure expressed in roentgens (R) of the ionization produced by photons (i.e., gamma and X-rays) in air.

film
In general, a "film packet" that contains one or more pieces of film in a light-tight wrapping. When developed, the film has an image caused by radiation that can be measured using an optical densitometer.

film dosimeter
A small packet of film within a holder that attaches to a wearer.

gamma rays

Electromagnetic radiation (photons) originating in atomic nuclei and accompanying many nuclear reactions (e.g., fission, radioactive decay, and neutron capture). Physically, gamma rays are identical to X-rays of high energy, the only essential difference being that X-rays do not originate in the nucleus.

isotope

Elements having the same atomic number but different atomic weights; identical chemically but having different physical and nuclear properties.

operating area

Designation of major onsite operational work areas.

radiation

Alpha, beta, neutron, and photon radiation.

radioactivity

The spontaneous emission of radiation, generally alpha or beta particles, gamma rays, and neutrons from unstable nuclei.

radionuclide

A radioactive isotope of an element, distinguished by atomic number, atomic weight, and energy state.

rem

A unit of dose equivalent equal to the product of the number of rad absorbed and the quality factor.

thermoluminescent dosimeter (TLD)

A holder containing solid chips of material that when heated will release stored energy as light. The measurement of this light provides a measurement of absorbed dose.

ATTACHMENT A
ESTIMATION OF PLUTONIUM AIR CONCENTRATIONS AT THE ROCKY FLATS PLANT
Page 1 of 22

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ATTACHMENT A
ESTIMATION OF PLUTONIUM AIR CONCENTRATIONS AT THE ROCKY FLATS PLANT

A.1 INTRODUCTION

Occupational environmental dose reconstruction for RFP requires that ^{239,240}Pu air concentrations be estimated for onsite locations as a function of time. Actual measurements of ^{239,240}Pu in air for the RFP onsite environment are generally preferable to modeled concentrations because modeling relies on measurements of parameters related to source terms and meteorology that are often spatially and temporally averaged, thus adding considerable uncertainty to estimates for particular locations or points in time. Further, models often cannot address all the processes or source terms that affect the air concentration. However, there are periods in the RFP operational history when useful measurements of ^{239,240}Pu in air are not available. This attachment describes the availability of monitoring data and modeled estimates and addresses the suitability of each type of estimate for use in occupational dose reconstruction for particular periods. In addition, it provides the technical basis of atmospheric transport calculations supporting the estimated ^{239,240}Pu intakes.

A.2 MEASUREMENT OF TOTAL LONG-LIVED ALPHA ACTIVITY AND PLUTONIUM IN AIR

Task 4 of the Phase II Historical Public Exposures Studies on RFP (Rope et al. 1999) contains an in-depth historical review and compilation of air monitoring data. This attachment relies on conclusions from that review to determine the usefulness of onsite air monitoring data in estimating ^{239,240}Pu intake from environmental (outdoor) exposures.

According to Rope et al. (1999), ^{239,240}Pu concentrations in air were not measured at RFP until 1969, when the Colorado Department of Health (now called the Colorado Department of Public Health and Environment) began reporting onsite air concentrations. Between the start of operations in 1952 and 1969, gross alpha activity in air was measured by the RFP contractor, but earlier data during this period (up to 1964) were considered by Rope et al. (1999, pp. III-33–III-34) to be of limited value for assessing concentrations of long-lived alpha emitters such as ^{239,240}Pu. Prior to 1960, measurements were not made in a way that enabled estimation of the long-lived alpha component of the gross alpha measurements. Thus, there is no reliable way to estimate ^{239,240}Pu in air before 1960 from air monitoring data. From 1960 to 1964, counts of gross alpha activity were made near the time of collection (4 hr after) and 1 wk later, such that TLLα activity concentrations could be estimated. Estimates of ^{239,240}Pu concentrations can be made from TLLα activity concentrations in a manner described later in this attachment. However, data collected between 1960 and 1964 were of limited value to the Task 4 studies because they were reported as one onsite number, with the maximum and minimum individual count values shown. Results from individual samplers could not be obtained. Thus, data before 1964 were not suitable or readily available for this TBD. Due to these inadequacies in monitoring data during the period between 1952 and 1964, this TBD relied on atmospheric dispersion modeling conducted for the Phase II study for developing estimates of ^{239,240}Pu concentrations in onsite air. This section describes the Phase II model and application for the present purposes.

From October 1964 until December 1971, the RFP contractor reported daily TLLα activity concentrations in air for individual onsite samplers (Rope et al. 1999, p. III-34). The samplers included S-1 through S-10, S-50, and S-51. The locations of the onsite samplers during this period are shown in the upper "1974" drawing in Figure A-1 (reproduced from Figure B-6 in Rope et al. 1999). Monthly average concentrations derived from these measurements, in fCi/m^3 (1×10^{-15} Ci/m^3),

are reproduced from Table B-6 in Rope et al. in Table A-1. (Note: Figures and tables appear at the end of this attachment.)

In 1969, the Colorado Department of Health began monitoring ^{239,240}Pu in air at the RFP (Rope et al. 1999, p. III-21) near the east security fence. Rope et al. (1999, p. III-23) used data from the CDPHE air monitoring stations to evaluate the predicted impact of contaminated soil after placement of the asphalt pad in the 903 Area. These measurements complement the air monitoring conducted by the RFP contractor and the Health and Safety Laboratory, which began monitoring air in the same vicinity (on the east security fence downwind of the 903 Area) in 1970 (Rope et al. 1999, p. III-12).

In 1970, the RFP environmental monitoring program began to include routine monitoring of ^{239,240}Pu in air (Rope et al. 1999, p III-63). However, results for ^{239,240}Pu, rather than TLLα, were not reported in RFP annual environmental reports until 1973 (Dow 1972a, 1973 to 1976; Rockwell 1977 to 1989; EG&G 1989 to 1993; Kaiser-Hill 1994). Table A-2 lists annual air concentrations, averaged over the onsite samplers and compiled from annual environmental reports through 1994 and the monthly data in Table A-1, along with the maximum onsite monthly measurement corresponding to that year. The units have been converted to femtocuries per cubic meter for consistency with Table A-1. Sampling locations are specified, and can be visualized from Figure A-1. The samplers were renumbered in 1975, as indicated in this figure. The annual average was not provided in the annual reports for 1977 to 1988, but was calculated from the monthly volume-weighted averages for each sampling location. Beginning in 1977, measurements were not reported for all samplers, but for sampling stations with the greatest potential for elevated airborne radioactivity. Thus, results after 1976 are not as representative of an average for the RFP industrial area, but for the onsite areas likely to be highest in concentrations of ^{239,240}Pu in air.

To estimate the ^{239,240}Pu air concentration based on TLLα activity concentration for data from 1965 to 1973 in Table A-2, a conversion factor was adopted from the review of available information on this topic provided in Rope et al. (1999, beginning on p. III-42). Rope et al. evaluated data collected in the early 1970s and derived a least-squares best fit to the data result of 36% plutonium contribution to the TLLα. Some of the TLLα activity in onsite air is due to naturally occurring alpha emitters and fallout plutonium. The remainder can be attributed to plutonium, americium, and uranium from RFP (Rope et al. 1999). A conversion factor of 0.36 was assumed for converting TLLα activity concentrations from the annual environmental reports to ^{239,240}Pu activity concentrations [10].

The annual environmental reports (Dow 1972a, 1973 to 1976; Rockwell 1977 to 1989; EG&G 1989 to 1993; Kaiser-Hill 1994) provide 95% CLs for the average annual ^{239,240}Pu air concentration for RFP for 1972 to 1976 and 1989 to 1994. For these years, the standard deviation was reported as the 95% CLs, assuming the measurements were normally distributed. In 1977 and 1978, no standard deviations were reported because “they can be misleading and (their use) is considered inappropriate for the data in this report” (Rockwell 1978, 1979). These two reports state that the sampling methods would result in “nonrandom variations in the measured concentrations,” and the “distribution … would not be normal.” Standard deviations are reported for 1979 to 1988, but only by sampler location, and not normalized to the site average. The CLs, when reported, are based on counting error alone, and thus represent the minimum error that can be associated with the measurements. Although counting error does contribute to uncertainty in the data, the uncertainty associated with a given average value for the site will also be a function of variability in environmental conditions as a function of time and

location. Thus, the reported CLs are not useful for estimating uncertainty associated with a site average because they would undoubtedly underestimate that uncertainty.

Annual environmental reports were discontinued after 1994 as a result of the change in the RFP mission, so site-wide measurements of ^{239,240}Pu in air after 1994 are not as readily accessible. Between 1995 and July 1998, onsite ambient air concentrations of ^{239,240}Pu are reported in RFETS EG&G and other Monthly and Quarterly Monitoring Reports (RMRS 1995a,b; RFETS 1996a to 1998d). In 1995, an onsite average air concentration can be calculated from the reported data for approximately 20 sampling locations, and a site-wide maximum annual average corresponding to the sampler at the location of highest concentration is also readily obtained. From 1996 to July 1998, air concentrations for only two samplers are reported, those samplers being at the point of highest air concentration based on monitoring in recent years. Thus, the air concentrations reported for those years tend to be more representative of maximum concentrations rather than site-wide averages. Annual air concentrations, averaged over all sampling locations, were calculated for 1995 through July 1998, and are listed in Table A-2. Site-wide maximum concentrations in Table A-2 correspond to the highest annual average concentration for any given sampler.

For the period from August 1998 to the present, onsite air concentrations are no longer reported directly in the Quarterly Reports However, CDPHE reported onsite concentrations in the eastern area of the industrial zone, where air concentrations tended to be highest (downwind of the contaminated soil area) from 1999 to the present. The concentrations reported by CDPHE are used to estimate site-wide maximum air concentrations for the post-1998 years, and are included in Table 4-3. Special project monitoring is carried out to monitor specific demolition and remediation activities. Formal reporting of this monitoring activity is currently being requested [11].

A.3 ATMOSPHERIC TRANSPORT MODELING

The atmospheric transport modeling results used to develop estimates of ^{239,240}Pu intake by workers between 1953 and 1964 relied on application of a model developed for the offsite risk assessment (Rood and Grogan 1999) [12]. Application of this model for onsite predictions was not the original intent, and simulated concentrations are considered less reliable than measured concentrations for estimates of ^{239,240}Pu intake for reasons stated in the introductory paragraph to this attachment. The application of this model for the Phase II Historical Public Exposures Studies focused on offsite rather than onsite concentrations, the latter being of interest here. However, the model application is such that building wake effects, a potential concern for areas close to the sources, are not going to be significant for two reasons. First, releases from the Building 771 stack are not likely to be affected by building wakes because the 44-m stack is sufficiently high, relative to nearby buildings, such that the plume is not significantly affected [13]. Second, all other elevated sources in the model were treated as area sources, such that initial dispersion was assigned, which implicitly accounts for the effects of building wakes [14].

Rood and Grogan (1999) described atmospheric transport modeling as follows (literature citations removed from quotation):

> *Atmospheric transport modeling performed in the Phase II studies used the Regional Atmospheric Transport Code for Hanford Environmental Tracking (RATCHET) model. Selection of RATCHET was based on a model comparison study performed for Phase II. In this study, five*

models, ranging in complexity from a simple straight-line Gaussian plume model (Industrial Source Complex Short Term Version 2) to a complex terrain model (Terrain-Responsive Atmospheric Code), were compared to tracer measurements taken during the 1991 Winter Validation Tracer Study. The results of this evaluation indicated no one model clearly outperformed the others. However, the puff trajectory models (RATCHET, TRIAD, and INPUFF2) generally had lower variability and higher correlation to observed values compared to the other models. The RATCHET model was chosen for these calculations because it incorporates spatially varying meteorological and environmental parameters. Additionally, the model includes modules that perform random sampling of the meteorological parameters, allowing for Monte Carlo analysis of uncertainty.

Atmospheric transport simulations were performed differently for discrete and continuous events. For discrete events, meteorological data for the specific days of the event were available. RATCHET was run using its Monte Carlo sampling features that sampled from distributions of basic transport parameters for each Monte Carlo trial. Transport parameters that were considered stochastically included wind speed, wind direction, mixing height, precipitation, and Monin-Obukhov scaling length. Uncertainty in the source term was also included in the simulation. Output consisted of n realizations of time-integrated concentration (TIC) and deposition at each of the 2295 computational nodes in the model domain (Figure 3).

Continuous events were modeled somewhat differently. Meteorological data from Rocky Flats for most of the assessment period were lacking. Therefore, we relied on a technique often used in prospective analysis and in retrospective analysis when historical records are lacking. This technique uses compilations of recently acquired meteorological data as a surrogate for past or future conditions and typically only applies to assessments of long-term (>1 year) dispersion conditions. We employed this technique for estimating annual average plutonium concentrations from routine releases and continuous 903 Area suspension releases using a 5-year data set from 1989 to 1993. Uncertainty was represented using several multiplicative correction factors that accounted for uncertainty in the dispersion process, meteorology, and deposition-plume depletion.

The model domain (Figure 3) encompasses a 2200 km^2 area (50 km north-south × 44 km east-west). The domain extends 28 km south, 12 km west, 22 km north, and 32 km east from the RFP. Most of the Denver metropolitan area and the city of Boulder are included in the domain.

The domain was limited in its western extent because few receptors were present there during the RFP operations and most of the contaminant plumes traveled east and southeast of the plant.

Figure 3 from Rood and Grogan (1999) is not reproduced here because of the irrelevance of much of the model domain to the present study. Rather, Figure A-2 shows the model domain of relevance, which is the RFP industrial area. There are six nodes in the industrial area, providing the ability to estimate six different air concentrations for these regions.

Discrete events in the Phase II studies were defined as those that led to releases of plutonium, which occurred over a relatively short period, and included releases from glovebox fires in 1957 and 1969 and suspension of plutonium-contaminated soil from the 903 Area during unusually high-wind events in 1968 and 1969. Continuous releases included “routine” releases from the Building 771 stack and Building 776 roof vents, and suspension of ^{239,240}Pu-contaminated soil from the 903 Area from 1964 to 1969, before the asphalt pad was in place, but did not include the above-noted high-wind events.

ATTACHMENT A
ESTIMATION OF PLUTONIUM AIR CONCENTRATIONS AT THE ROCKY FLATS PLANT

Resuspension of ^{239,240}Pu deposited on soil from 903 Area suspension releases and other routine and nonroutine events was included in the comprehensive evaluation of exposure to ^{239,240}Pu released from RFP (Rood and Grogan 1999). A time-dependent factor approach was used to address the resuspension of soil contaminated by released ^{239,240}Pu and deposited as a result of the continuous and discrete events. Rood and Grogan (1999, p. 17) describe the source term characterization.

Aerodynamic diameter of ^{239,240}Pu particles released is important in predicting dispersion and deposition and ultimately in estimating the respirable fraction of the ^{239,240}Pu in air. The source terms characterized for the Phase II studies considered potential size distributions, and the predictive modeling addressed differential dispersion and deposition according to particle size. Thus, results of the modeling enabled prediction of the ^{239,240}Pu concentration in air associated with respirable particles.

Comparisons of model output for the RFP onsite and perimeter regions to air monitoring data from onsite and perimeter samplers, respectively, were made to determine the adequacy of the predictive results in representing concentrations to which RFP workers might have been exposed. Figure A-3 plots the annual average ^{239,240}Pu concentrations in air as a function of time in the RFP industrial area from 1953 to 1990. Model-predicted concentrations represent the average of the six onsite computational nodes shown in Figure A-2, and are for particles less than 30-μm AED. Figure A-4 plots annual average ^{239,240}Pu concentrations in air as a function of time for the perimeter area of the Plant from 1953 through 1989. For perimeter locations, model-predicted concentrations represent the average of 27 computational nodes, shown in Figure A-5. The 5th-, 50th-, and 95th-percentile concentrations for 500 realizations for each of these model applications are shown for the period from 1953 to 1989.

Measured data shown in Figure A-3 represent the average concentrations across the onsite samplers listed in the legend. Samplers S-1 to S-10, S-50, and S-51 were maintained by an RFP contractor throughout the period of interest. The annual average TLLα data from 1965 through 1972, calculated from the data in Table A-1, were converted to ^{239,240}Pu concentrations for comparison to the model predictions. A conversion factor of 0.36 (0.36 Ci ^{239,240}Pu per Ci TLLα) reported in Figure III-23 in Rope et al. (1999) was used [15]. Average concentrations from samplers S-5 to S-9 were obtained from Table B-10 in Rope et al. (1999), which is reproduced in Table A-3. The onsite values in this table tend to be slightly higher than the averages in Table A-2 because they are restricted to samplers S-5 to S-9 only for all years. Figure A-3 also plots the arithmetic average of measurements obtained by CDPHE samplers D-3, D-4, and AP-56, located at the eastern security fence of RFP (Figure A-6). The data from which averages were derived for these CDPHE samplers are listed in Table A-4, which was reproduced from Table III-4 in Rope et al. (1999).

From Figure A-3, it is clear that the modeled 50th-percentile concentrations can underpredict the measured concentrations, especially after about 1970. Before 1970, agreement between model predictions and measured concentrations is fairly good. One possible explanation for underprediction that does not necessarily render modeling as an underprediction of ^{239,240}Pu intake at RFP is that reported ^{239,240}Pu concentrations are often at locations of expected elevated concentrations, while the modeled concentrations are averages for the entire site. After 1970, the main source of plutonium to onsite air was resuspension of contaminated soil (Rood and Grogan 1999, p. 57); thus, one would expect air concentrations in the area of highest soil plutonium (downwind of the 903 Area) to be higher than the site average. Because the measured data predominantly arose from that area

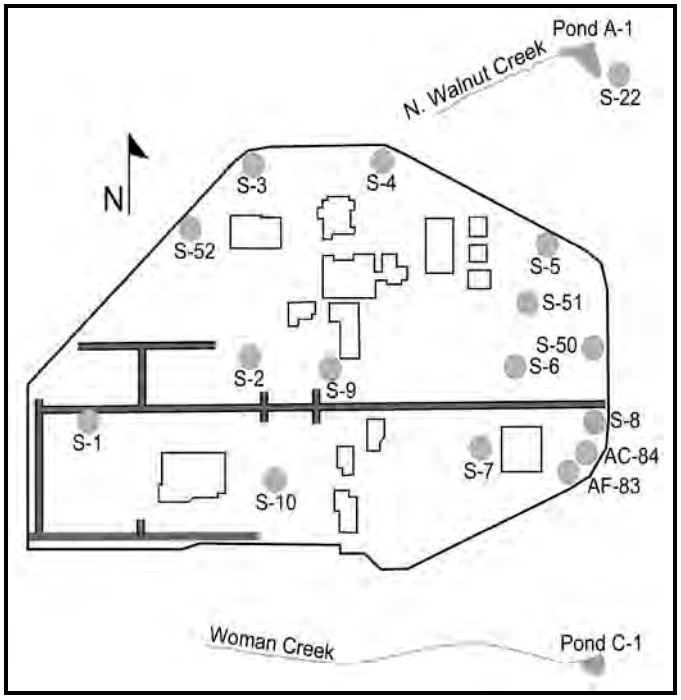
(samplers S-5 through S-9), it is likely that measured concentrations would exceed the site average. It is not necessarily likely, however, that an exposed individual would spend a significant amount of time in an area of higher ^{239,240}Pu concentration in air. Thus, the model might be a more reasonable predictor of average dose for an individual exposed to average concentrations across the site, rather than in the areas of higher ^{239,240}Pu concentration.

Measured data shown in Figure A-4 for the perimeter concentrations were obtained from the 1971 to 1990 annual environmental reports prepared by RFP contractors and represent average concentrations from RFP contractor perimeter samplers, shown in Figure A-7 as triangular symbols. These data were corrected for contributions from background ^{239,240}Pu because the measured values are low enough that fallout concentrations can contribute a significant portion of the total measurement. Yearly measurements of ^{239,240}Pu in air in Denver (Rope et al. 1999, Table B-14, reproduced in Table A-5) were assumed to be representative of RFP background levels [16]. These levels were subtracted from the perimeter measurements in Table A-3 to obtain the average net perimeter ^{239,240}Pu concentrations listed in Table A-6 and plotted in Figure A-4. From Figure A-4, it is clear that the model predictions and measured concentrations are in good agreement for these perimeter locations.

The results of these comparisons of model predictions with measured ^{239,240}Pu concentrations support the following conclusions. Onsite application of the atmospheric dispersion model developed for the Phase II historical offsite exposure studies must be done with caution. Predicted average onsite concentrations might not adequately represent actual concentrations of interest due to the large spatial variation in soil and, thus, air contamination at the site. While it is desirable to use measured concentrations from the many air samplers across the site to derive average and maximum values, some of the historical data to support this are not readily available or of sufficient quality. Therefore, it is reasonable, especially before 1970, to use the Phase II model application for estimating onsite average concentrations in lieu of measurement data.

ATTACHMENT A
ESTIMATION OF PLUTONIUM AIR CONCENTRATIONS AT THE ROCKY FLATS PLANT

1974



1975

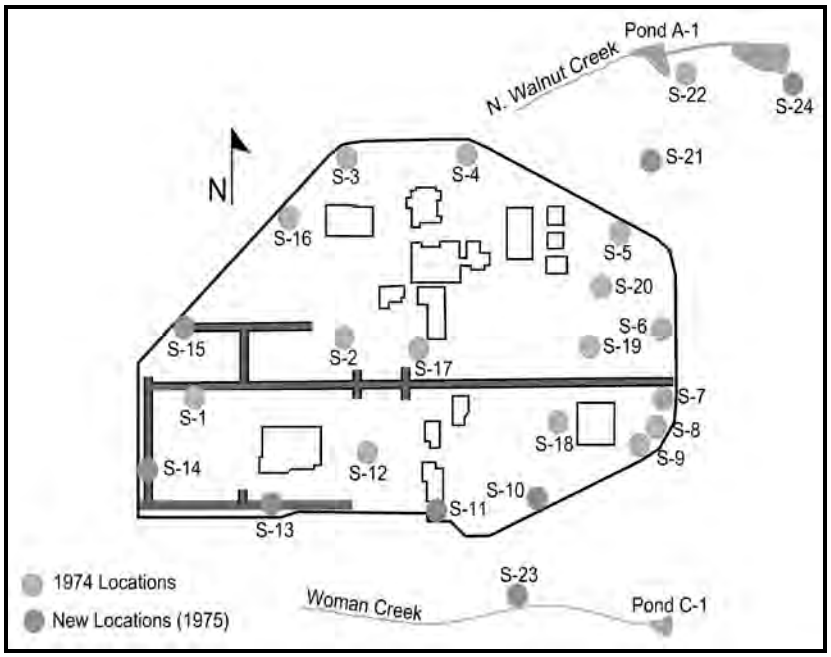


Figure A-1. Locations of samplers operated by RFP contractor. In 1975, samplers were renumbered and new samplers were added. (Reproduced from Rope et al. 1999, Figure B-6).

ATTACHMENT A
ESTIMATION OF PLUTONIUM AIR CONCENTRATIONS AT THE ROCKY FLATS PLANT
Page 9 of 22

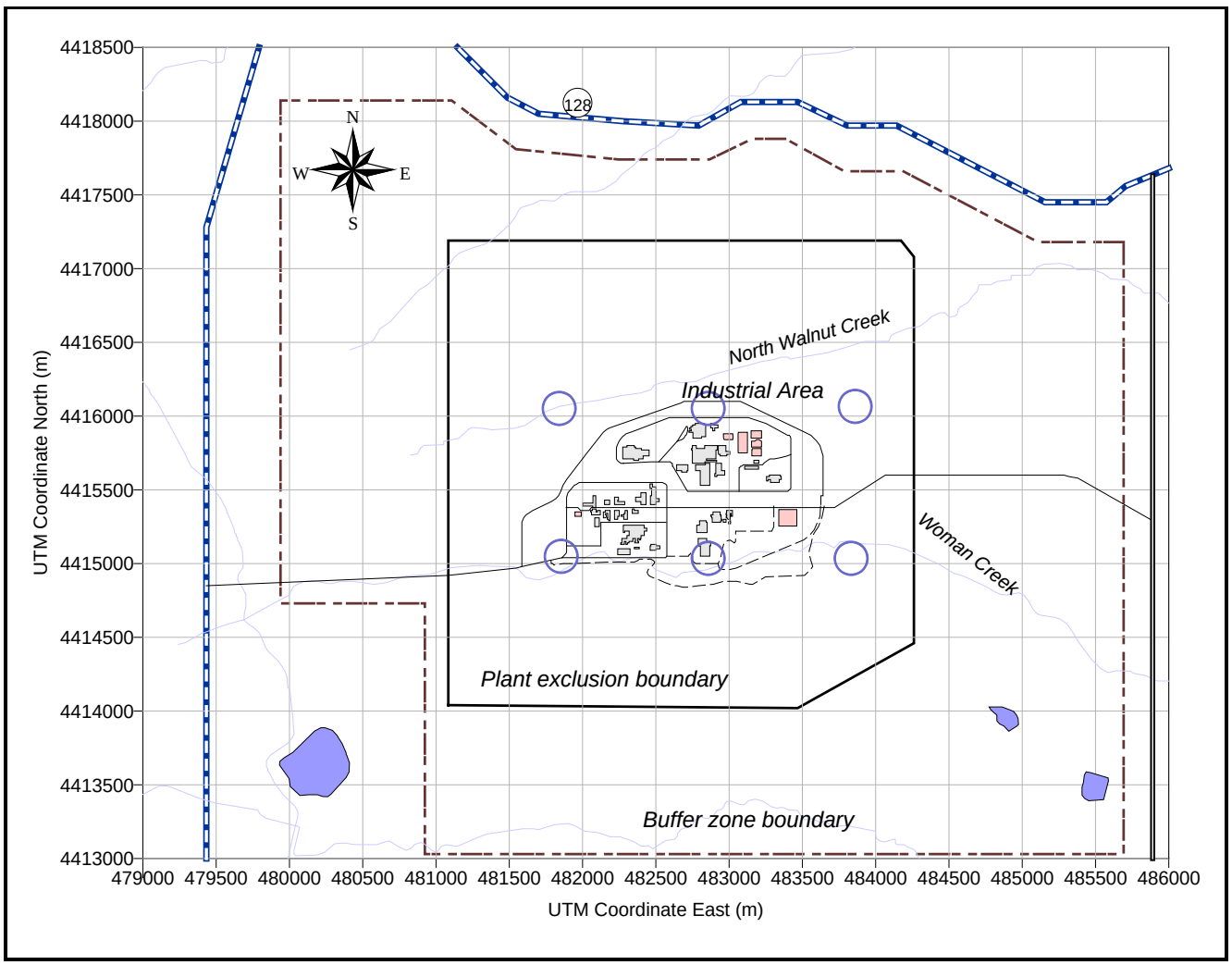


Figure A-2. Location of onsite (industrial area) computational nodes (circles) used to predict average onsite air concentrations for RFP industrial area.

ATTACHMENT A
ESTIMATION OF PLUTONIUM AIR CONCENTRATIONS AT THE ROCKY FLATS PLANT
Page 10 of 22

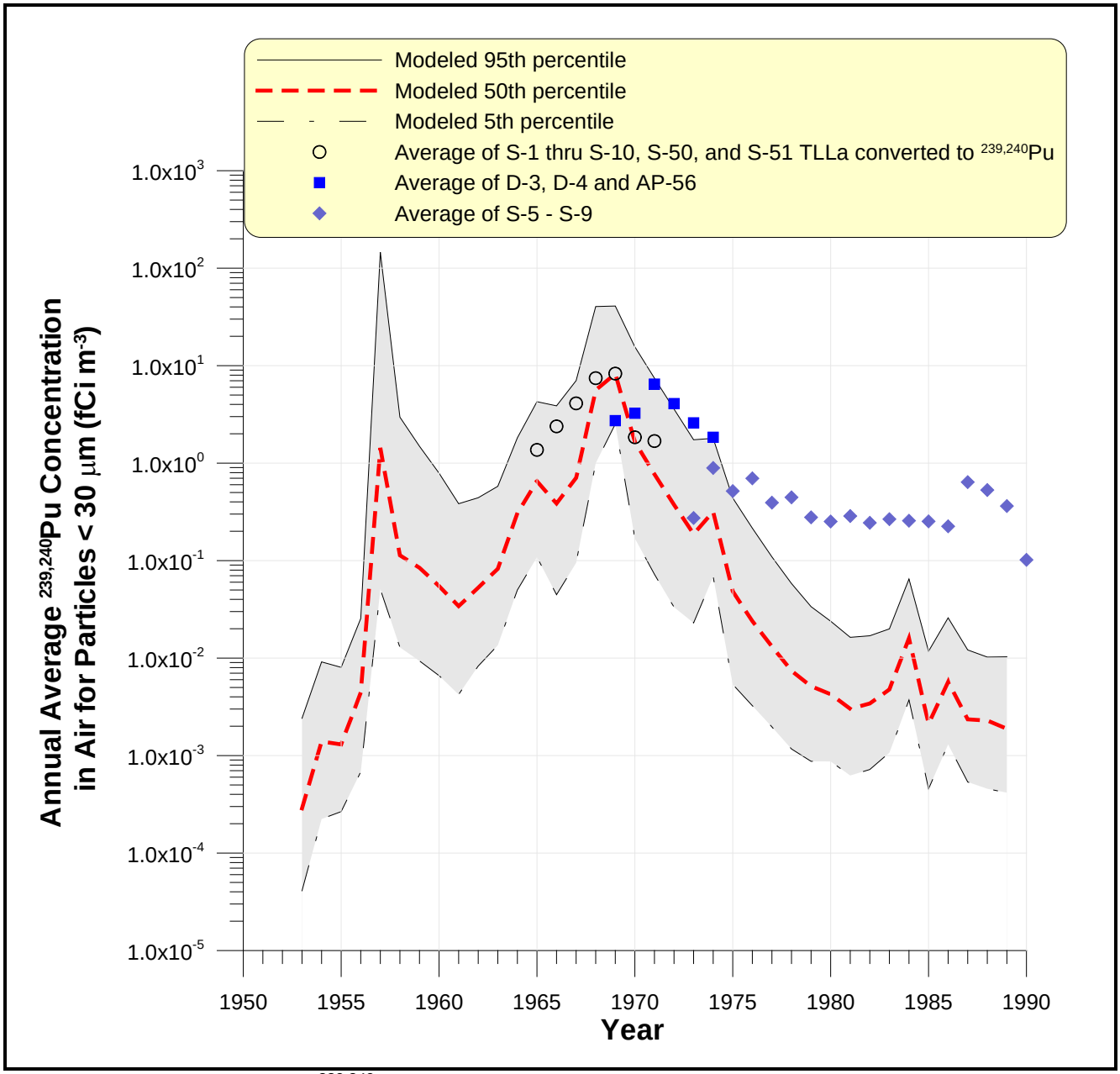


Figure A-3. Annual average ^{239,240}Pu concentrations in air as a function of time for particles < 30-μm AED in RFP industrial area. [Model-predicted concentrations represent the average of six onsite computational nodes as shown in Figure A-3 using the model described in Rood and Grogan (1999).]

ATTACHMENT A
ESTIMATION OF PLUTONIUM AIR CONCENTRATIONS AT THE ROCKY FLATS PLANT
Page 11 of 22

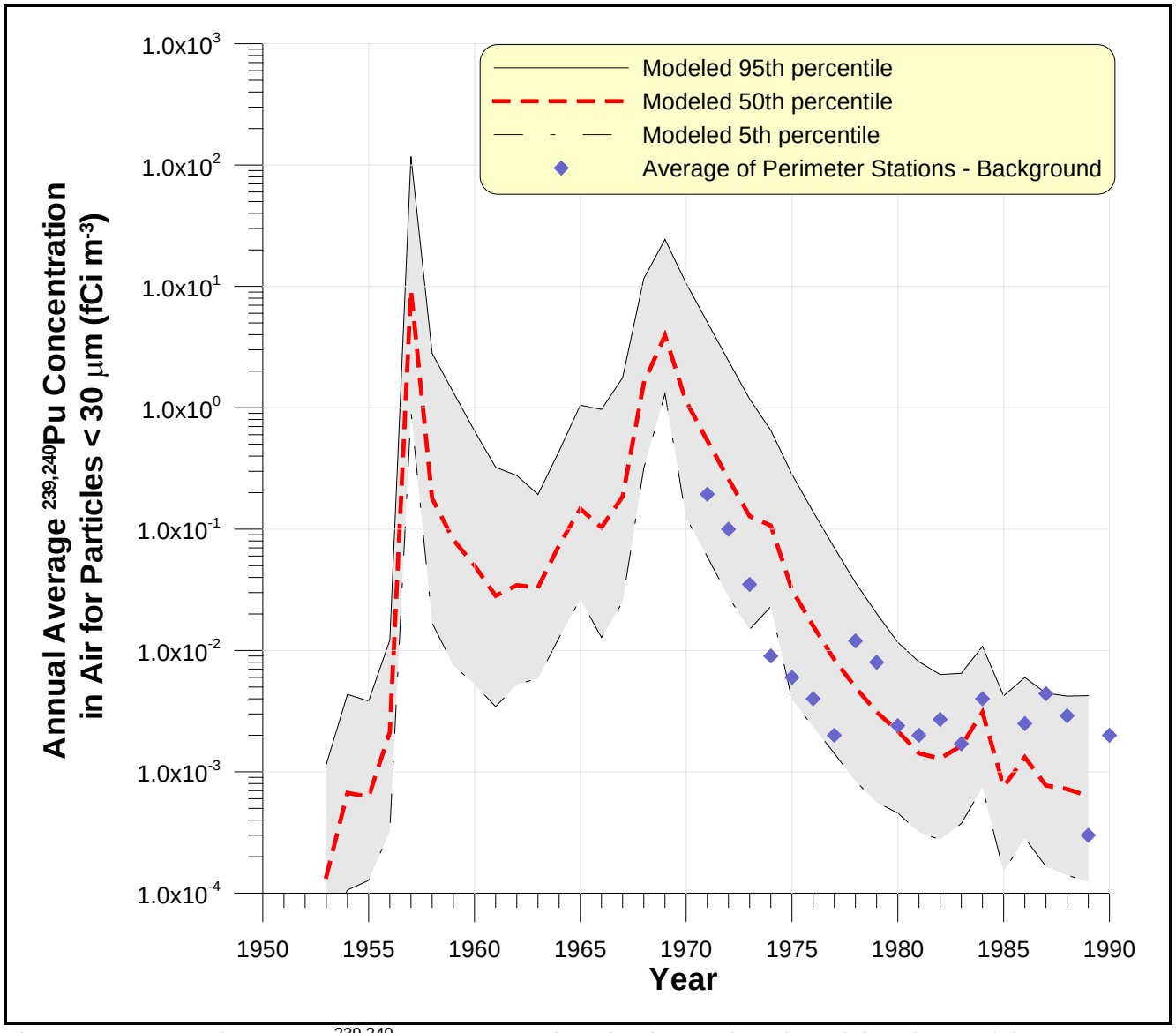


Figure A-4. Annual average ^{239,240}Pu concentrations in air as a function of time for particles < 30-μm AED in the perimeter area surrounding RFP. [Model-predicted concentrations represent the average of 27 computational nodes as shown in Figure A-7 using the model described in Rood and Grogan (1999).]

ATTACHMENT A
ESTIMATION OF PLUTONIUM AIR CONCENTRATIONS AT THE ROCKY FLATS PLANT
Page 12 of 22

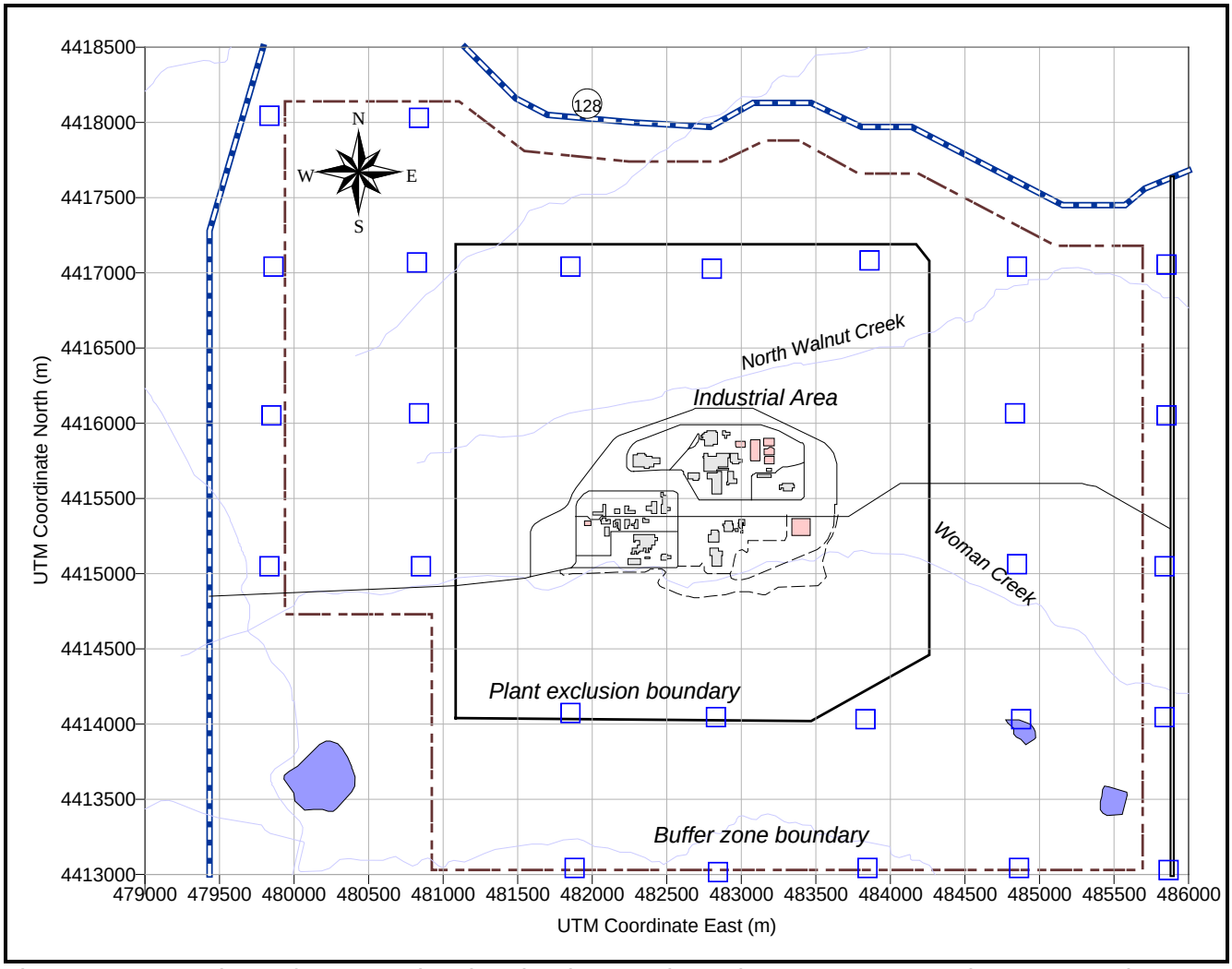


Figure A-5. Locations of computational nodes (squares) used to compute annual average perimeter concentrations shown in Figure A-6.

ATTACHMENT A
ESTIMATION OF PLUTONIUM AIR CONCENTRATIONS AT THE ROCKY FLATS PLANT
Page 13 of 22

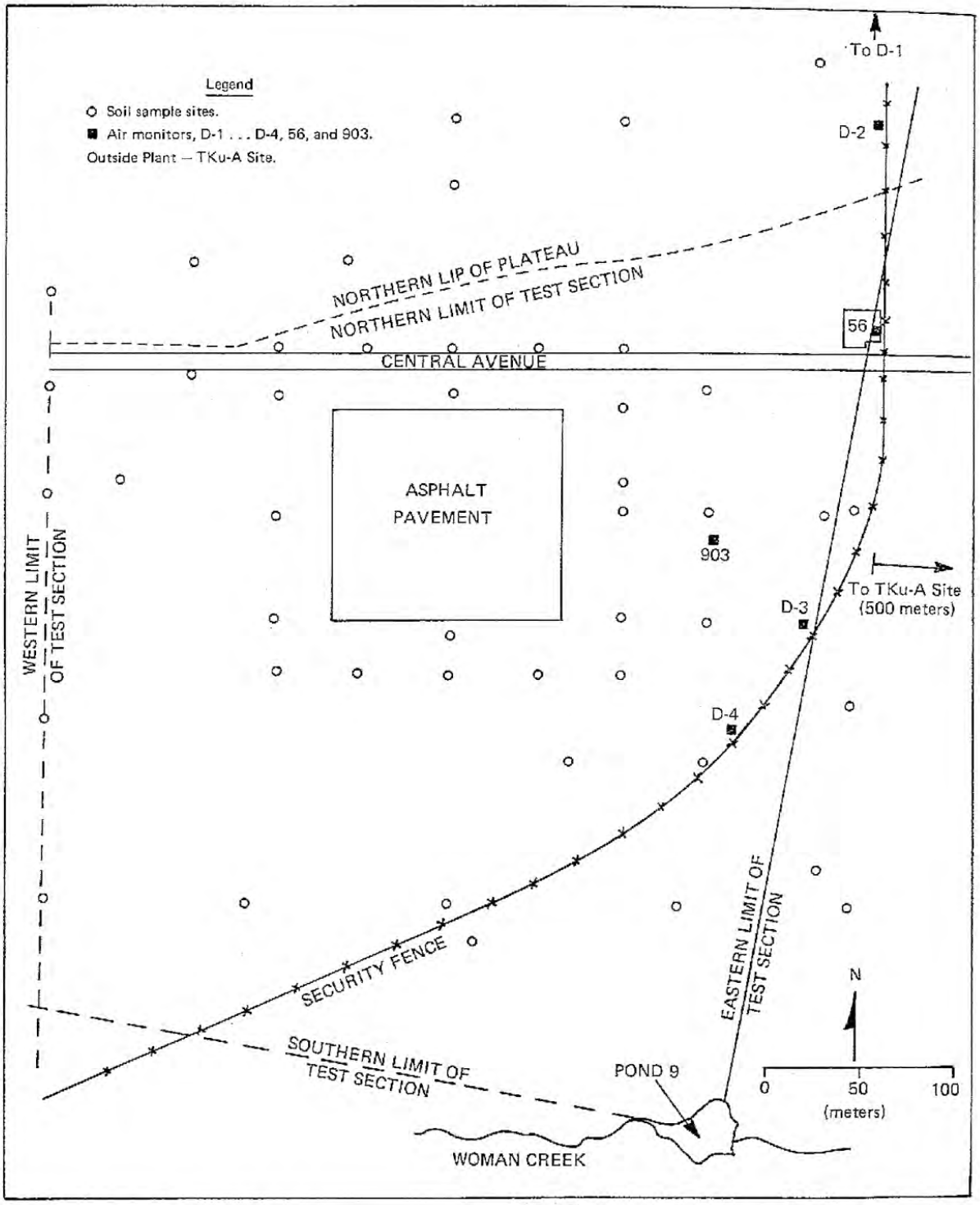


Figure A-6. Eastern part of RFP industrial area, showing locations of CDPHE air monitoring stations D-1 to D-5. Sampler AP-56 is believed to be north of Central Avenue near the security fence. [Reproduced from Figure III-13 of Rope et al. (1999).]

ATTACHMENT A
ESTIMATION OF PLUTONIUM AIR CONCENTRATIONS AT THE ROCKY FLATS PLANT
Page 14 of 22

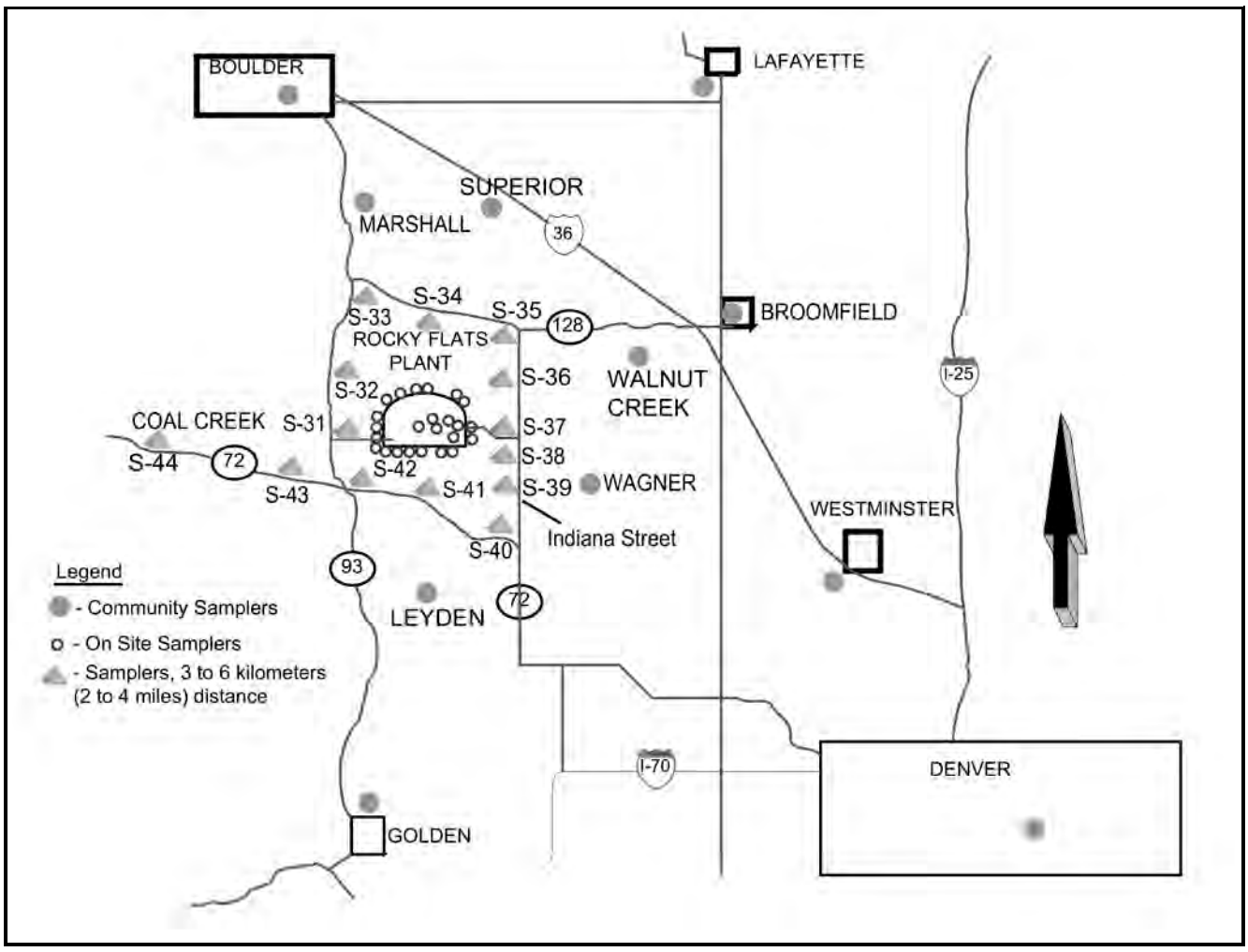


Figure A-7. Locations of offsite air samplers in 1975 (Figure B-4 from Rope et al. 1999).

ATTACHMENT A
ESTIMATION OF PLUTONIUM AIR CONCENTRATIONS AT THE ROCKY FLATS PLANT
Page 15 of 22

Table A-1. Monthly average concentrations (fCi/m^3) of total long-lived alpha activity in onsite air samples, October 1964 to December 1971 [reproduced from Table B-6 in Rope et al. (1999); reconstructed from daily measurements]. Blank indicates sampler not in operation.

Month	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9	S-10	S-50	S-51
Oct 64	2	6	2	4	4	3	3	11	6	4		
Nov 64	1	2	6	1	2	2	2	16	3	2		
Dec 64	2	3	4	2	7	4	3	79	4	3		
Jan 65	2	2	11	3	7	2	2	8	3	2		
Feb 65	3	2	2	4	4	4	3	4	2	3		
Mar 65	5	3	3	5	3	5	2	2	3	3		
Apr 65	5	3	2	2	2	3	3	5	2	2		
May 65	3	13	1	3	4	5	3	4	2	3		
Jun 65	4	2	2	2	4	5	2	8	2	2		
Jul 65	4	2	2	2	3	6	2	9	1	3		
Aug 65	4	1	2	3	3	4	2	5	2	3		
Sep 65	5	3	3	3	7	5	0	5	2	4		
Oct 65	3	3	3	1	2	4	2	3	3	2		
Nov 65	10	3	3	2	4	4	2	9	3	4		
Dec 65	4	7	7	6	14	13	5	7	4	9		
Jan 66	11	6	4	2	8	4	3	12	6	14		
Feb 66	3	2	3	5	6	2	1	11	3	4		
Mar 66	4	2	4	3	3	3	2	11	5	3		
Apr 66	3	2	3	4	4	4	2	6	3	2		
May 66	4	4	4	3	6	5	5	5	7	7		
Jun 66	7	5	4	2	3	13	8	12	6	8		
Jul 66	7	6	4	4	6	6	5	11	7	6		
Aug 66	15	7	4	12	7	11	8	13	8	6		
Sep 66	28	8	9	12	18	16	5	10	7	8		
Oct 66	11	4	4	7	8	8	9	10	7	4		
Nov 66	7	2	3	16	8	6	6	13	5	3		
Dec 66	7	4	5	14	10	12	4	8	8	6		
Jan 67	8	4	7	15	13	7	6	22	23	8		
Feb 67	5	6	6	22	8	8	13	38	6	4		
Mar 67	6	1	5	11	7	8	5	9	5	3		
Apr 67	3	3	6	6	10	7	3	11	5	7		
May 67	9	4	7	8	9	12	8	9	6	5		
Jun 67	10	5	8	13	14	11	17	18	5	5		
Jul 67	15	5	7	8	11	14	28	19	9	3		
Aug 67	27	6	15	10	11	17	28	26	10	12		
Sep 67	5	3	3	6	4	14	14	22	4	5		
Oct 67	5	3	7	7	5	15	24	99		7		
Nov 67	6	5	10	6	4	9	8	49		7		
Dec 67	9	7	17	7	3	3	9	92		4		
Jan 68	8	4	12	5	6	3	8	29		5		
Feb 68	15	9	23	12	7	6	10	33		11		
Mar 68	14	18	22	8	9	17	11	116		28		
Apr 68	16	11	13	9	6	27	31	182		10		

ATTACHMENT A
ESTIMATION OF PLUTONIUM AIR CONCENTRATIONS AT THE ROCKY FLATS PLANT
Page 16 of 22

Table A-1 (Continued). Monthly average concentrations (fCi/m^3) of total long-lived alpha activity in onsite air samples, October 1964 to December 1971 [reproduced from Table B-6 in Rope et al. (1999); reconstructed from daily measurements]. Blank indicates sampler not in operation.

Month	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9	S-10	S-50	S-51
May 68	8	9	17	10	7	21	70	155		8		
Jun 68	6	6	8	12	4	51	68	110		18		
Jul 68	5	4	7	4	4	14	14	31		3		
Aug 68	9	6	8	5	7	9	10	17		4		
Sep 68	6	6	7	5	5	4	9	50		3		
Oct 68	12	7	8	6	4	11	19	33		3	7	11
Nov 68	7	4	6	3	7	9	6	168		4	4	2
Dec 68	11	6	4	8	6	6	20	357		3	11	3
Jan 69	10	6	9	7	10	15	127	1525		3	7	5
Feb 69	6	4	8	5	5	4	23	129		3	4	3
Mar 69	7	4	3	5	4	2	4	208		2	5	3
Apr 69	7	3	5	3	6	3	22	148	4	4	5	6
May 69	5	11	9	9	9	17	21	28	10	6	9	6
Jun 69	4	4	7	4	4	7	9	68	4	4	7	3
Jul 69	15	7	7	7	4	20	7	20	4	4	11	6
Aug 69	4	6	5	6	5	7	7	22	5	3	6	9
Sep 69	6	6	5	5	6	5	6	19	4	3	5	5
Oct 69	6	3	5	18	3	5	3	12	2	3	3	3
Nov 69	3	2	4	5	4	3	2	12	2	3	4	4
Dec 69	5	4	5	7	4	2	4	32	7	5	4	4
Jan 70	3	2	4	4	4	3	3	12	3	4	2	3
Feb 70	2	4	5	4	3	4	13	33	3	6	2	7
Mar 70	3	4	4	15	3	5	4	10	4	4	3	5
Apr 70	10	5	5	7	9	7	5	7	2	3	5	3
May 70	9	4	5	3	4	4	2	10	1	4	4	4
Jun 70	14	7	12	9	57	13	7	10	4	13	7	10
Jul 70	7	5	1	3	2	2	2	4	3	3	4	4
Aug 70	3	4	2	3	2	4	10	4	3	4	2	5
Sep 70	2	6	6	3	3	3	3	5	3	4	4	4
Oct 70	5	3	5	4	3	4	2	5	3	4	3	4
Nov 70	2	6	3	3	5	4	1	3	2	2	4	2
Dec 70	3	4	3	3	3	3	6	5	2	3	4	2
Jan 71	4	4	3	2	3	4	7	5	4	4	4	4
Feb 71	3	4	2	4	4	3	6	7	4	5	3	5
Mar 71	5	4	4	5	3	3	8	8	4	5	8	4
Apr 71	4	4	5	7	4	3	3	26	4	5	5	5
May 71	5	4	5	3	4	6	4	9	4	5	5	4
Jun 71	4	3	4	5	5	4	4	10	4	7	7	4
Jul 71	4	3	5	4	4	12	3	12	3	2	4	2
Aug 71	4	4	6	4	3	3	4	8	4	3	9	4
Sep 71	5	3	6	3	3	3	2	6	3	4	6	3

ATTACHMENT A
ESTIMATION OF PLUTONIUM AIR CONCENTRATIONS AT THE ROCKY FLATS PLANT

Table A-1 (Continued). Monthly average concentrations (fCi/m^3) of total long-lived alpha activity in onsite air samples, October 1964 to December 1971 [reproduced from Table B-6 in Rope et al. (1999); reconstructed from daily measurements].

Month	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9	S-10	S-50	S-51
Oct 71	5	4	4	3	6	3	2	12	2	5	7	5
Nov 71	3	4	6	3	5	5	3	10	2	4	5	4
Dec 71	4	5	4	3	3	4	4	6	3	4	5	4

ATTACHMENT A
ESTIMATION OF PLUTONIUM AIR CONCENTRATIONS AT THE ROCKY FLATS PLANT

Table A-2. Estimated annual average concentrations (fCi/m^3) of ^{239,240}Pu in onsite air samples between 1965 and 1994[a] based on measurement data provided in Table A-1, RFP annual environmental reports, RFETS monthly and quarterly monitoring reports, and CDPHE quarterly environmental surveillance reports.

Year	Sampling location[b]	Type of measurement	Conversion factor to ^{239,240}Pu[c]	Annual average air concentration (fCi/m^3)	Maximum air concentration[d] (fCi/m^3)
1965	S1-S10	TLLα	0.36	1[e]	2[e]
1966	S1-S10	TLLα	0.36	2[e]	4[e]
1967	S1-S10	TLLα	0.36	4[e]	12[e]
1968	S1-S8, S10	TLLα	0.36	7[e]	38[e]
1969	S1-S10, S50-S51	TLLα	0.36	8[e]	67[e]
1970	S1-S10, S50-S51	TLLα	0.36	2[e]	3[e]
1971	S1-S10, S50-S51	TLLα	0.36	2[e]	4[e]
1972	S1-S10, S50-S51	TLLα	0.36	<2.1	3.9
1973	S1-S10, S50-S52	TLLα	0.36	<2.2	<3.9
1973	S1-S10, S50-S52	Pu-239,240	1	<1.2	<6.5
1974	S1-S10, S50-S52	Pu-239,240	1	0.6	3.2
1975	S1-S10, S22, S50-S52, Af83, Ac84	Pu-239,240	1	<0.2	1.0
1976	S1-S24	Pu-239,240	1	0.2	1.4
1977	S1-S24	Pu-239,240	1	0.3[f]	0.6
1978	S5-S9, S19-S21	Pu-239,240	1	0.3[f]	0.9
1979	S2, S5-S9,S15-S16, S19-S21	Pu-239,240	1	0.2[f]	0.5
1980	S5-S9, S16, S19-S21	Pu-239,240	1	0.2[f]	0.5
1981	S5-S9, S16, S19-S21	Pu-239,240	1	0.2[f]	0.5
1982	S5-S9, S16, S19-S21	Pu-239,240	1	0.3[f,g]	0.5
1983	S5-S9	Pu-239,240	1	0.2[f,g]	0.4
1984	S5-S9	Pu-239,240	1	0.3[f,g]	0.6
1985	S5-S9	Pu-239,240	1	0.2[f,g]	0.4
1986	S5-S9	Pu-239,240	1	0.3[f,g]	0.5
1987	S5-S9	Pu-239,240	1	0.7[f,g]	1.2
1988	S5-S9	Pu-239,240	1	0.5[f,g]	0.7
1989	S5-S9	Pu-239,240	1	0.4	0.5
1990	S1-S24, S88	Pu-239,240	1	0.1	0.9
1991	S1-S25	Pu-239,240	1	0.1	1.2
1992	S1-S25	Pu-239,240	1	0.1	0.6
1993	S3-S25	Pu-239,240	1	0.1	0.4
1994	S3-S25	Pu-239,240	1	0.1	0.4
1995[h]	S005–S007, S009, S101-104, S106, S107, S109, S110, S112, S116, S119, S121, S123, S202–S206, S208, S211	Pu-239,240	1	0.02	0.2
1996[h]	S007, S107	Pu-239,240	1	0.08	0.08
1997[h]	S007, S107	Pu-239,240	1	0.05	0.07
1998[h,i]	S007, S107	Pu-239,240	1	0.080	0.1
1999[j,k]	D-1,D-3	Pu-239,240	1	0.07	0.1
2000[j]	D-1,D-3	Pu-239,240	1	0.08	0.1
2001[j]	D-1,D-3	Pu-239,240	1	0.08	0.2
2002[j]	D-1,D-3	Pu-239,240	1	0.03	0.05
2003[j]	D-1,D-3	Pu-239,240	1	0.09	0.2
2004[j]	D-1	Pu-239,240	1	0.03	0.03
2005[j,l]	D-1	Pu-239,240	1	0.1	0.1

a. Compiled from measurement data in Dow (1972a, 1973 to 1975); Rockwell (1976 to 1989); EG&G (1989 to 1993); and Kaiser-Hill (1994), unless otherwise noted.
b. Refer to Figure A-1 for samplers through 1994; after 1994, see monthly and quarterly monitoring reports for maps.
c. Based on Rope et al. (1999, pp. III-42 – III-46).
d. The maximum monthly concentration at any one sampling location.
e. Calculated from data in Table A-1.
f. Calculated by averaging reported annual volume-weighted average concentration for each sampler.
g. Results only reported for samplers in area of higher measured plutonium air concentrations for RFP.
h. From RFETS quarterly environmental monitoring reports (RFETS 1995a,b,c, 1996a,b,c, 1998a,b).
i. Based on data collected January through July 1998.
j. From CDPHE quarterly environmental surveillance reports (CDPHE 2000 to 2005b).
k. Based on last 3 quarters only.
l. Based on first 2 quarters only.

ATTACHMENT A
ESTIMATION OF PLUTONIUM AIR CONCENTRATIONS AT THE ROCKY FLATS PLANT

Table A-3. Annual average concentrations (fCi-m^3) of plutonium in air for three location groups, RFP contractor monitoring, 1971 to 1990[a] [reproduced from Table B-10 in Rope et al. (1999)]. Blank indicates no sampler.

Year	Onsite[b]	Perimeter	Community
1971		0.26	
1972		0.14	
1973	0.274	0.05	0.26
1974	0.892	0.058	0.34
1975	0.517	0.037	0.031
1976	0.698	0.015	0.013
1977	0.393	0.038	0.037
1978	0.446	0.06	0.06
1979	0.278	0.02	0.02
1980	0.252	0.01	0.01
1981	0.287	0.018	0.019
1982	0.244	0.005	0.006
1983	0.226	0.003	0.007
1984	0.257	0.005	0.005
1985	0.235	0.002	0.002
1986	0.225	0.005	0.003
1987	0.639	0.005	0.003
1988	0.529	0.003	0.002
1989	0.363	0.001	0.001
1990	0.102	0.002	0.001

a. Obtained from RFP contractor annual reports. Data are plotted as a line chart in Rope et al. (1999, Chapter III).
b. Onsite samples are the average of locations S–5, S–6, S–7, S–8, and S–9, as numbered in 1975.

ATTACHMENT A
ESTIMATION OF PLUTONIUM AIR CONCENTRATIONS AT THE ROCKY FLATS PLANT
Page 20 of 22

Table A-4. Data from Table III-4 in Rope et al. (1999) showing a comparison of $^{239,240}Pu$ concentrations (fCi/m^3) in onsite and offsite air, measured by CDPHE. Blank – no data.

Location	1969	1970	1971	1972	1973	1974
Onsite						
D-1		0.29	0.31	1.44	0.74	0.44
D-2		0.37	0.34	0.69	0.62	0.73
D-3		6.29	10.29	4.47	2.87	3.77
D-4		2.21	7.34	5.48	4.63	1.33
APC-56	2.73	1.25	1.77	2.28	0.28	0.43
Onsite average[a]	**2.73**	**2.08**	**4.01**	**2.87**	**1.83**	**1.34**
Offsite (metro):						
D-5 (SE boundary)		0.16	0.13	0.12	0.10	0.10
APC-2 Denver (EPA data)[b]	0.070	0.077	0.066	0.040	0.015	0.049
APC-15 Arvada		0.16	<0.08	0.06	<0.06	0.25
APC-16 Golden	0.08	<0.11	0.08	<0.06	<0.06	<0.08
APC-19 Boulder		0.13	<0.07	<0.05	<0.06	<0.06
APC-22 Longmont	0.08	0.12	0.07	<0.02	<0.05	<0.1
Offsite (metro) average[a]	**0.08**	**0.13**	**0.08**	**0.06**	**0.06**	**0.12**
Offsite (remote):						
APC-29 Durango				<0.12	<0.02	<0.05
APC-42 Fort Collins				<0.04	<0.08	0.14
APC-81 Walsenburg				0.07	<0.06	0.38
APC-108 Rangely				0.1	<0.08	0.13
Offsite (remote) average[b]				**0.08**	**0.06**	**0.18**

a. Averages in this table are arithmetic averages of the annual averages from each station.
b. Lower minimum detectable concentration for EPA data (0.001 compared to 0.08 for APC-x stations and 0.03 for D-x stations).

ATTACHMENT A
ESTIMATION OF PLUTONIUM AIR CONCENTRATIONS AT THE ROCKY FLATS PLANT
Page 21 of 22

Table A-5. Data from Table B-14 in Rope et al. (1999) showing annual average concentrations (fCi/m^3) of $^{239,240}Pu$ in Denver air, 1971 to 1989.

Year	Average	5th percentile	95th percentile	Method of determination[a]
1971	6.6E-2	5.3E-2	7.9E-2	M
1972	4.0E-2	3.2E-2	4.8E-2	M
1973	1.5E-2	1.2E-2	1.8E-2	M
1974	4.9E-2	3.9E-2	5.9E-2	M
1975	3.1E-2	2.5E-2	3.7E-2	M
1976	1.1E-2	9.0E-3	1.3E-2	M
1977	3.6E-2	2.8E-2	4.0E-2	M
1978	4.8E-2	3.8E-2	5.7E-2	M
1979	1.2E-2	9.3E-3	1.4E-2	M
1980	7.6E-3	3.8E-3	1.1E-2	M
1981	1.6E-2	3.8E-3	1.1E-2	N
1982	2.3E-3	8.0E-3	2.4E-2	N
1983	1.3E-3	6.5E-4	2.0E-3	M
1984	1.0E-3	5.0E-4	1.5E-3	M
1985	4.0E-3	2.3E-3	6.8E-3	M
1986	2.5E-3	1.2E-3	3.7E-3	M
1987	6.0E-4	3.0E-4	9.0E-4	M
1988	1.0E-4	5.0E-5	1.5E-4	M
1989	7.0E-4	3.5E-4	1.0E-3	M

a. M = average of values measured by the Public Health Service or EPA in Denver for that year. See Figure III-7 and associated text in Rope et al. (1999) for additional discussion.

ATTACHMENT A
ESTIMATION OF PLUTONIUM AIR CONCENTRATIONS AT THE ROCKY FLATS PLANT

Table A-6. Corrected annual average concentrations of $^{239,240}Pu$ in air at perimeter monitoring stations (from Table B-10 in Rope et al. 1999).

Year	Pu-239, -240 concentration (fCi/m^3)[a]	Net Pu-239, -240 concentration (fCi/m^3)[b]
1971	2.60E-01	1.94E-01
1972	1.40E-01	1.00E-01
1973	5.00E-02	3.50E-02
1974	5.80E-02	9.00E-03
1975	3.70E-02	6.00E-03
1976	1.50E-02	4.00E-03
1977	3.80E-02	2.00E-03
1978	6.00E-02	1.20E-02
1979	2.00E-02	8.00E-03
1980	1.00E-02	2.40E-03
1981	1.80E-02	2.00E-03
1982	5.00E-03	2.70E-03
1983	3.00E-03	1.70E-03
1984	5.00E-03	4.00E-03
1985	2.00E-03	0.00E+00[c]
1986	5.00E-03	2.50E-03
1987	5.00E-03	4.40E-03
1988	3.00E-03	2.90E-03
1989	1.00E-03	3.00E-04
1990	2.00E-03	2.00E-03

a. From Table A-3.
b. The net concentration is the concentration in the second column minus the corresponding average background value reported in Table A-5.
c. Average background measurement (Table A-5) exceeded measured perimeter value.

ATTACHMENT B
SCREENING OF RADIONUCLIDE SOURCE TERMS
FOR ENVIRONMENTAL DOSE EVALUATION
Page 1 of 8

TABLE OF CONTENTS

LIST OF TABLES

ATTACHMENT B
SCREENING OF RADIONUCLIDE SOURCE TERMS
FOR ENVIRONMENTAL DOSE EVALUATION

B.1 SCREENING METHODOLOGY

To evaluate the potential importance of the radionuclides other than plutonium isotopes reported to have been released to the air at RFP since operations began in 1952, information from Phase I and Phase II of the Historical Public Exposure Studies on RFP (ChemRisk 1994a; Rood and Grogan 1999) were used to estimate maximum historical onsite yearly inhalation doses for the radionuclides identified. Radionuclides were considered insignificant contributors to dose if estimated maximum committed dose for a 1-yr intake associated with the release was on the order of 1 mrem or less for the period of interest [17].

The source terms described in Phase I were assumed to be reasonable estimates of the releases of tritium, depleted uranium, enriched uranium, and ^{241}Am [18]. For Phase I, effluent monitoring data reported by RFP was reviewed and determined to provide a good basis for estimating airborne releases of all radionuclides with the exception of believed under-reporting of uranium emissions prior to 1961 (ChemRisk 1994a, p. 9). Emissions for uranium were reconstructed from raw data found in logbooks in the Denver Federal Records Center (ChemRisk 1994a, p. 75). For the period before 1978, "total long-lived alpha radioactivity measured from facilities which process depleted uranium was assumed to represent depleted uranium and total long-lived alpha radioactivity measured from facilities which process enriched uranium was assumed to represent enriched uranium" (ChemRisk 1994a, p. 113). It is important to note that the release estimates reported here do not appear to include emissions from the 903 Area, which occur as a result of suspension of the primary contamination (i.e., oil-contaminated soil), or resuspension of the windblown material deposited downwind. Thus, this component of the emissions of ^{241}Am is not fully evaluated here, and is addressed in the Occupational Environmental Dose section.

To calculate an estimated maximum committed dose for a 1-yr intake from these releases, the 95th-percentile release rates were multiplied by the maximum predicted normalized air concentration (χ/Q), in s/m^3, to obtain the maximum onsite air concentration for each radionuclide. The χ/Q value was obtained from atmospheric dispersion modeling done in *Phase II Comprehensive Assessment of Exposure and Lifetime Cancer Incidence Risk from Plutonium Released from the Rocky Flats Plant, 1953-1989* (Rood and Grogan 1999), where all identified sources of plutonium were considered together to develop plutonium air concentration profiles of the RFP vicinity. The maximum χ/Q value for the industrial area and buffer zone was selected for estimating annual air concentrations. The model predicted a maximum χ/Q of 6.28×10^{-6} s/m^3 at a computational node in the north-central portion of the industrial area of the site.

Calculated annual air concentrations were multiplied by an inhalation rate of 2,400 m^3/yr, representing a 2,000-hr work year and 1.2 m^3/hr inhalation rate to obtain an estimate of annual radionuclide intake. The maximum annual intake for each radionuclide was multiplied by its respective inhalation dose factor from ICRP Publication 68 to obtain an estimate of maximum committed dose for a 1-yr intake (ICRP 2001).

B.2 TRITIUM

Tritium is known to have been released during routine RFP operations and accidents. Routine releases were reported in annual reports after 1973 (ChemRisk 1994b) and were estimated to be less

than 10 Ci/yr. Several larger releases of tritium were documented and reviewed in the Phase I study. The three most significant incidents with respect to tritium release occurred in 1968, 1973, and 1974. The highest estimated release of tritium cited in the Phase I study occurred in the 1973 accident, where it was reported that as much as 350 to 1,600 Ci of tritium were released in exhausted air from Building 779A.

The estimated annual releases (Q) of tritium, in curies per year, from the Phase I study are listed in Table B-1. This table includes the inhalation dose factor assumed for tritium (ICRP 2001) and the calculated dose for each year. (Note: All tables appear at the end of this attachment.) For screening purposes, this inhalation factor corresponds to the highest value reported for all forms of tritium compounds (ICRP 2001), representing inhalation of organically bound tritium compounds, and is approximately 2.3 times higher than the value for tritiated water vapor. While this is clearly an overestimate of the dose factor for the most likely form of tritium (water vapor), it was chosen to offset the uncertainty in the χ/Q value used, which might not accurately estimate the true normalized air concentration for tritiated water vapor because it assumes the emitted compounds are particulate. Dry deposition of tritium is not like that of other radiological species due to its association with water vapor (O'Kula and Murphy 2001). From Table B-1, the maximum dose was calculated for 1953 to 1989 to be less than 1 mrem/yr. Thus, tritium was an insignificant contributor to inhalation dose based on the criterion put forth in the first paragraph of this attachment, and is not addressed further in this TBD.

B.3 DEPLETED AND ENRICHED URANIUM

Uranium was processed at RFP in two forms: depleted and enriched. Release estimates in the Phase I studies (ChemRisk 1994b) were developed for both forms. Until 1978, estimated release of both forms rely on measurements of TLLα because routine isotopic analyses of effluent sample filters from uranium facilities were not performed until that time. After 1978, not all uranium isotopes of interest were routinely measured. Thus, the Phase I analysis based estimates on known alpha activity fractions for the two types of uranium.

Approximately 15 mCi of depleted uranium and 7 mCi of enriched uranium were released to the RFP air environment between 1953 and 1989. According to the ChemRisk (1994b) analysis, more than 90% of the activity released is estimated to have occurred before 1970, with the highest releases in the 1950s.

The estimated annual releases (Q) of depleted and enriched uranium, in microcuries per year, from the Phase I study are listed in Tables B-2 and B-3. These tables include the inhalation dose factor assumed for the two forms of uranium and the calculated doses for each year. The dose factor used is the maximum dose factor associated with airborne particulate uranium isotopes (i.e., that for 0.3-µm AMAD ^{234}U, of absorption type S) included in depleted and enriched uranium, and applies to the organ receiving the highest dose (lungs). From Tables B-2 and B-3, the maximum doses calculated for 1953 to 1989 for both forms of uranium were always less than 1 mrem/yr with one exception. In 1955, a maximum dose of 1.2 mrem is predicted for depleted uranium. In light of the dose-maximizing assumptions made in these calculations, it is not expected that intakes of released depleted or enriched uranium realistically exceeded 1 mrem/yr; thus, depleted and enriched uranium were considered insignificant contributors to inhalation dose and are not addressed further in this TBD.

ATTACHMENT B
SCREENING OF RADIONUCLIDE SOURCE TERMS
FOR ENVIRONMENTAL DOSE EVALUATION

This conclusion is supported by the conclusions of the analysis by Voillequé (1999d) in the Phase II study, which found that releases of enriched and depleted uranium at RFP pose substantially less risk (in terms of radiological dose) than plutonium releases.

B.4 AMERICIUM-241

Americium-241, a decay product of ^{241}Pu, exists as an undesirable contaminant in weapons-grade plutonium. Although RFP plutonium initially contained about 0.0001% ^{241}Am (ChemRisk 1994b, p. 106), the ^{241}Am-to-$^{239/240}$Pu ratio increases over time due to decay of ^{241}Pu. Not until 1985 were ^{241}Am effluents routinely monitored at RFP. Thus, an estimate of the release rate of this isotope from all possible sources requires assumptions regarding the ratio of its activity to other alpha emitters for which activity was measured. Based on data for 1985 to 1989, the average ratio of ^{241}Am-to-$^{239/240}$Pu emissions was about 22% (ChemRisk 1994b, p. 110). Therefore, the Phase I work assumed that this ratio existed throughout the entire operational period of the facility to derive estimated releases of ^{241}Am, in microcuries per year, listed in Table B-4. This assumption might not be realistic if efforts were made to separate the ^{241}Am from the plutonium being processed, but it is likely more applicable to resuspension releases of this isotope that occur years after the plutonium was deposited on the soil.

Table B-4 estimates show peak ^{241}Am releases occurring in 1957 (because the peak $^{239/240}$Pu releases occurred during that year from the 1957 fire) and dropping off dramatically since 1976. A total of 11 mCi is calculated to have been released, with 34% of that in 1957.

Table B-4 includes the inhalation dose factor assumed for ^{241}Am (ICRP 2001) and the calculated dose for each year. The inhalation dose factor was maximized by assuming a particulate AMAD of 0.3 µm, absorption type M, and the organ receiving the highest dose (bone surfaces). From Table B-4, the maximum dose was calculated for 1953 to 1989 to be approximately 34 mrem/yr in 1957. Thus, ^{241}Am was considered a potentially significant contributor to inhalation dose based on the criterion in the first paragraph of this attachment, and is addressed as such in this TBD.

ATTACHMENT B
SCREENING OF RADIONUCLIDE SOURCE TERMS
FOR ENVIRONMENTAL DOSE EVALUATION
Page 5 of 8

Table B-1. Maximum estimated committed doses for tritium by year.

Year	Annual tritium release[a]		95% CL calculated air concentration[b] (μCi/m^3)	Maximum tritium dose[c] (mrem/yr)
	GM (Ci/yr)	95% CL (Ci/yr)		
1953	NA	8.00E+02	1.59E-04	5.8E-02
1954	NA	8.00E+02	1.59E-04	5.8E-02
1955	NA	8.00E+02	1.59E-04	5.8E-02
1956	NA	8.00E+02	1.59E-04	5.8E-02
1957	NA	8.00E+02	1.59E-04	5.8E-02
1958	NA	8.00E+02	1.59E-04	5.8E-02
1959	NA	8.00E+02	1.59E-04	5.8E-02
1960	NA	8.00E+02	1.59E-04	5.8E-02
1961	NA	8.00E+02	1.59E-04	5.8E-02
1962	NA	8.00E+02	1.59E-04	5.8E-02
1963	NA	8.00E+02	1.59E-04	5.8E-02
1964	NA	8.00E+02	1.59E-04	5.8E-02
1965	NA	8.00E+02	1.59E-04	5.8E-02
1966	NA	8.00E+02	1.59E-04	5.8E-02
1967	NA	8.00E+02	1.59E-04	5.8E-02
1968	NA	3.90E+02	7.76E-05	5.8E-02
1969	NA	3.90E+02	7.76E-05	2.8E-02
1970	NA	3.90E+02	7.76E-05	2.8E-02
1971	NA	3.90E+02	7.76E-05	2.8E-02
1972	NA	3.90E+02	7.76E-05	2.8E-02
1973	NA	3.90E+02	7.76E-05	2.8E-02
1974	2.50E+01	5.70E+01	1.13E-05	2.8E-02
1975	3.90E+00	8.80E+00	1.75E-06	4.1E-03
1976	3.10E+00	7.00E+00	1.39E-06	6.4E-04
1977	1.40E+00	3.10E+00	6.17E-07	5.1E-04
1978	2.30E+00	5.30E+00	1.06E-06	2.2E-04
1979	2.20E+00	4.90E+00	9.75E-07	3.8E-04
1980	2.00E+00	4.60E+00	9.16E-07	3.6E-04
1981	1.10E+00	2.60E+00	5.18E-07	3.3E-04
1982	6.00E-01	1.40E+00	2.79E-07	1.9E-04
1983	4.20E-01	9.40E-01	1.87E-07	1.0E-04
1984	3.60E-01	8.20E-01	1.63E-07	6.8E-05
1985	4.20E-01	9.40E-01	1.87E-07	5.9E-05
1986	5.70E-01	1.30E+00	2.59E-07	6.8E-05
1987	4.40E-01	9.90E-01	1.97E-07	9.4E-05
1988	6.80E-02	1.50E-01	2.99E-08	7.2E-05
1989	4.40E-01	9.90E-01	1.97E-07	1.1E-05

a. From Phase I studies (ChemRisk 1994b).
b. Based on maximum χ/Q of 6.28×10^{-6} s/m^3.
c. Assuming dose factor of 1.52×10^{-1} mrem/μCi and intake rate of 2,400 m^3/yr.

ATTACHMENT B
SCREENING OF RADIONUCLIDE SOURCE TERMS
FOR ENVIRONMENTAL DOSE EVALUATION

Table B-2. Maximum estimated committed doses for depleted uranium, by year.

Year	Annual depleted uranium release[a]		95% CL calculated air concentration[b] (µCi/m^3)	Maximum depleted uranium dose[c] (mrem/yr)
	GM (µCi/yr)	95% CL (µCi/yr)		
1953	1.60E+03	4.00E+03	7.96E-10	7.0E-01
1954	1.60E+03	4.00E+03	7.96E-10	7.0E-01
1955	2.70E+03	7.00E+03	1.39E-09	1.2E+00
1956	1.30E+03	3.30E+03	6.57E-10	5.8E-01
1957	9.50E+02	2.40E+03	4.78E-10	4.2E-01
1958	2.10E+03	5.30E+03	1.06E-09	9.3E-01
1959	3.50E+02	9.00E+02	1.79E-10	1.6E-01
1960	4.60E+02	1.20E+03	2.39E-10	2.1E-01
1961	6.80E+02	1.70E+03	3.38E-10	3.0E-01
1962	4.80E+02	1.20E+03	2.39E-10	2.1E-01
1963	6.40E+02	1.60E+03	3.19E-10	2.8E-01
1964	3.10E+02	8.00E+02	1.59E-10	1.4E-01
1965	3.60E+02	9.30E+02	1.85E-10	1.6E-01
1966	1.80E+02	4.70E+02	9.36E-11	8.2E-02
1967	1.80E+02	4.70E+02	9.36E-11	8.2E-02
1968	1.80E+02	4.70E+02	9.36E-11	8.2E-02
1969	2.10E+02	5.30E+02	1.06E-10	9.3E-02
1970	2.50E+02	6.30E+02	1.25E-10	1.1E-01
1971	7.50E+01	1.90E+02	3.78E-11	3.3E-02
1972	5.50E+01	1.40E+02	2.79E-11	2.4E-02
1973	7.00E+01	1.80E+02	3.58E-11	3.1E-02
1974	1.20E+01	3.00E+01	5.97E-12	5.2E-03
1975	3.60E+01	9.30E+01	1.85E-11	1.6E-02
1976	1.60E+01	4.00E+01	7.96E-12	7.0E-03
1977	2.50E+01	6.30E+01	1.25E-11	1.1E-02
1978	4.30E+01	1.10E+02	2.19E-11	1.9E-02
1979	3.40E+01	8.70E+01	1.73E-11	1.5E-02
1980	2.00E+01	5.00E+01	9.95E-12	8.7E-03
1981	2.30E+01	6.00E+01	1.19E-11	1.0E-02
1982	2.50E+01	6.30E+01	1.25E-11	1.1E-02
1983	4.00E+01	1.00E+02	1.99E-11	1.7E-02
1984	7.20E+00	1.80E+01	3.58E-12	3.1E-03
1985	5.10E+01	1.30E+02	2.59E-11	2.3E-02
1986	3.80E+00	9.70E+00	1.93E-12	1.7E-03
1987	1.60E+01	4.00E+01	7.96E-12	7.0E-03
1988	1.20E+01	3.10E+01	6.17E-12	5.4E-03
1989	3.30E+00	8.30E+00	1.65E-12	1.5E-03

a. From Phase I studies (ChemRisk 1994b).
b. Based on maximum χ/Q of 6.28×10^{-6} s/m^3.
c. Assuming U-234 organ dose factor of 3.66×10^5 mrem/µCi and intake rate of 2,400 m^3/yr.

ATTACHMENT B
SCREENING OF RADIONUCLIDE SOURCE TERMS
FOR ENVIRONMENTAL DOSE EVALUATION
Page 7 of 8

Table B-3. Maximum estimated committed doses for enriched uranium by year.

Year	Annual enriched uranium release[a]		95% CL calculated air concentration[b] (µCi/m^3)	Maximum enriched uranium dose[c] (mrem/yr)
	GM (µCi/yr)	95% CL (µCi/yr)		
1953	1.20E+01	3.00E+01	5.97E-12	5.2E-03
1954	1.20E+01	3.00E+01	5.97E-12	5.2E-03
1955	9.60E+01	2.50E+02	4.98E-11	4.4E-02
1956	1.40E+03	3.70E+03	7.37E-10	6.5E-01
1957	4.70E+02	1.20E+03	2.39E-10	2.1E-01
1958	4.00E+02	1.00E+03	1.99E-10	1.7E-01
1959	7.00E+02	1.80E+03	3.58E-10	3.1E-01
1960	1.10E+03	2.90E+03	5.77E-10	5.1E-01
1961	6.20E+02	1.60E+03	3.19E-10	2.8E-01
1962	3.20E+02	8.30E+02	1.65E-10	1.5E-01
1963	4.30E+02	1.10E+03	2.19E-10	1.9E-01
1964	2.50E+02	6.30E+02	1.25E-10	1.1E-01
1965	2.50E+02	6.30E+02	1.25E-10	1.1E-01
1966	3.00E+02	7.70E+02	1.53E-10	1.3E-01
1967	1.40E+02	3.70E+02	7.37E-11	6.5E-02
1968	2.10E+02	5.30E+02	1.06E-10	9.3E-02
1969	6.50E+01	1.70E+02	3.38E-11	3.0E-02
1970	8.30E+01	2.10E+02	4.18E-11	3.7E-02
1971	5.30E+01	1.40E+02	2.79E-11	2.4E-02
1972	5.20E+00	1.30E+01	2.59E-12	2.3E-03
1973	1.60E+01	4.00E+01	7.96E-12	7.0E-03
1974	3.50E+01	9.00E+01	1.79E-11	1.6E-02
1975	3.60E+01	9.30E+01	1.85E-11	1.6E-02
1976	2.10E+01	5.30E+01	1.06E-11	9.3E-03
1977	2.70E+01	7.00E+01	1.39E-11	1.2E-02
1978	2.70E+01	7.00E+01	1.39E-11	1.2E-02
1979	1.20E+01	3.10E+01	6.17E-12	5.4E-03
1980	2.00E+01	5.00E+01	9.95E-12	8.7E-03
1981	1.60E+01	4.00E+01	7.96E-12	7.0E-03
1982	1.60E+01	4.00E+01	7.96E-12	7.0E-03
1983	2.60E+01	6.70E+01	1.33E-11	1.2E-02
1984	2.60E+01	6.70E+01	1.33E-11	1.2E-02
1985	1.00E+01	2.60E+01	5.18E-12	4.5E-03
1986	1.40E+01	3.70E+01	7.37E-12	6.5E-03
1987	6.00E+00	1.50E+01	2.99E-12	2.6E-03
1988	3.40E+00	8.70E+00	1.73E-12	1.5E-03
1989	6.80E+00	1.70E+01	3.38E-12	3.0E-03

a. From Phase I studies (ChemRisk 1994b).
b. Based on maximum χ/Q of 6.28×10^{-6} s/m^3.
c. Assuming U-234 organ dose factor of 3.66×10^5 mrem/µCi and intake rate of 2,400 m^3/yr.

ATTACHMENT B
SCREENING OF RADIONUCLIDE SOURCE TERMS
FOR ENVIRONMENTAL DOSE EVALUATION

Table B-4. Maximum estimated committed doses for ^{241}Am by year.

Year	Annual Am-241 release[a]		95% CL calculated air concentration[b] (µCi/m^3)	Maximum Am-241 dose[c] (mrem/yr)
	GM (µCi/yr)	95% CL (µCi/yr)		
1953	5.00E-01	1.30E+00	2.59E-13	4.6E-03
1954	1.70E+01	4.30E+01	8.56E-12	1.5E-01
1955	1.80E+01	4.70E+01	9.36E-12	1.7E-01
1956	5.70E+01	1.50E+02	2.99E-11	5.3E-01
1957	3.80E+03	9.70E+03	1.93E-09	3.4E+01
1958	7.80E+02	2.00E+03	3.98E-10	7.1E+00
1959	3.50E+02	9.00E+02	1.79E-10	3.2E+00
1960	3.20E+02	8.20E+02	1.63E-10	2.9E+00
1961	3.80E+02	9.70E+02	1.93E-10	3.4E+00
1962	7.60E+02	1.90E+03	3.78E-10	6.7E+00
1963	9.10E+02	2.30E+03	4.58E-10	8.1E+00
1964	7.00E+02	1.80E+03	3.58E-10	6.4E+00
1965	1.70E+03	4.30E+03	8.56E-10	1.5E+01
1966	8.10E+01	2.10E+02	4.18E-11	7.4E-01
1967	1.00E+02	2.60E+02	5.18E-11	9.2E-01
1968	1.20E+02	3.20E+02	6.37E-11	1.1E+00
1969	3.50E+02	9.00E+02	1.79E-10	3.2E+00
1970	9.50E+01	2.40E+02	4.78E-11	8.5E-01
1971	1.80E+01	4.70E+01	9.36E-12	1.7E-01
1972	1.50E+01	3.90E+01	7.76E-12	1.4E-01
1973	1.50E+01	3.90E+01	7.76E-12	1.4E-01
1974	2.90E+02	7.50E+02	1.49E-10	2.7E+00
1975	3.10E+01	7.90E+01	1.57E-11	2.8E-01
1976	1.20E+00	3.20E+00	6.37E-13	1.1E-02
1977	1.20E+00	3.20E+00	6.37E-13	1.1E-02
1978	8.70E-01	2.20E+00	4.38E-13	7.8E-03
1979	1.70E+00	4.30E+00	8.56E-13	1.5E-02
1980	3.60E+00	9.30E+00	1.85E-12	3.3E-02
1981	2.50E+00	6.50E+00	1.29E-12	2.3E-02
1982	6.20E+00	1.60E+01	3.19E-12	5.7E-02
1983	2.40E+01	6.10E+01	1.21E-11	2.2E-01
1984	2.40E+01	6.10E+01	1.21E-11	2.2E-01
1985	2.80E+00	7.20E+00	1.43E-12	2.5E-02
1986	1.30E+01	3.30E+01	6.57E-12	1.2E-01
1987	4.50E+00	1.20E+01	2.39E-12	4.2E-02
1988	2.80E+00	7.20E+00	1.43E-12	2.5E-02
1989	1.50E+00	3.90E+00	7.76E-13	1.4E-02

a. From Phase I studies (ChemRisk 1994b).
b. Based on maximum χ/Q of 6.28×10^{-6} s/m^3.
c. Assuming organ dose factor of 7.40×10^6 mrem/µCi and intake rate of 2,400 m^3/yr.