DOE Review Release: 04/24/2020

Weldon Spring Plant – Occupational Environmental Dose

ORAUT-TKBS-0028-4 Rev. 04
Effective Date: 03/27/2020
Supersedes: Revision 03

Subject Expert(s): David P. Harrison

Document Owner Approval:	Signature on File David P. Harrison, Document Owner	Approval Date:	03/25/2020
Concurrence:	Signature on File John M. Byrne, Objective 1 Manager	Concurrence Date:	03/25/2020
Concurrence:	Signature on File Scott R. Siebert, Objective 3 Manager	Concurrence Date:	03/25/2020
Concurrence:	Vickie S. Short Signature on File for Kate Kimpan, Project Director	Concurrence Date:	03/25/2020
Approval:	Signature on File Timothy D. Taulbee, Associate Director of Science	Approval Date:	03/27/2020

FOR DOCUMENTS MARKED AS A TOTAL REWRITE, REVISION, OR PAGE CHANGE, REPLACE THE PRIOR REVISION AND DISCARD / DESTROY ALL COPIES OF THE PRIOR REVISION.

☐ New ☒ Total Rewrite ☐ Revision ☐ Page Change

PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
06/28/2005	00	First approved issue of new technical basis document for the Weldon Spring Plant – Occupational Environmental Dose. Incorporates formal internal and NIOSH review comments. Training is not required. Initiated by Robert Meyer.
05/17/2013	01	Revision initiated to revise the TBD as a result of completion of Advisory Board Work Group issues. Included information in Section 4.2.2.1 about the drying of the raffinate pits and its potential for resuspension of pit radionuclide content. Included factors for calculation of recycled uranium contaminant activity based on ppb or pCi uranium. Revised and implemented according to ORAUT-PROC-0031, Rev. 02. Added a table for maximum sitewide median intake values to comply with PROC-0031, and also added a table of annual median intake values for the WSCP, WSRP, and WSQ. Replaced introductory text with updated template language in Section 4.1. Revised Section 4.1.1, Purpose, and Section 4.1.2, Scope. Revised Sections 4.2.1 and 4.2.2 to more specifically target the radionuclides of concern and source terms that contribute to 95% of the potential internal dose. Revised the approach to determination of annual intake of radionuclides (Section 4.2.3.1) during the operational period to optimize the use of available site-specific monitoring data. Added a table of annual median values for occupational external dose to be used as surrogates for onsite ambient dose during the operational period. Added Section 4.4 as a summary of environmental doses for use by dose reconstructors and provided tabulated inhalation intakes and ambient dose default values. Incorporates formal internal and NIOSH review comments. Constitutes a total rewrite of the document. Training required: As determined by the Objective Manager. Initiated by David P. Harrison.
03/29/2017	02	Revision initiated to refer to ORAUT-TKBS-0017-5, *Feed Materials Production Center – Occupational Internal Dose*, in relation to RU contaminants and their mass concentrations. Section 4.2.4 was added which includes a table of ratios of RU contaminant intake activity per unit activity uranium, Bq/Bq U. Table for maximum annual median intakes was changed to include the additional RU contaminants. Includes editorial changes. Incorporates formal internal and NIOSH review comments. Constitutes a total rewrite of the document. Training required: As determined by the Objective Manager. Initiated by David P. Harrison.
09/08/2017	03	Revision initiated to incorporate SC&A comments regarding the date stated for work containing recycled uranium (from 1961 and on). Changes were made in Section 4.2.2.1. Updated references in the text and in the Reference Section. Added and deleted some acronyms and abbreviations from the listing. No sections were deleted. No changes were needed as a result of formal internal review. Incorporates formal NIOSH review comments. Training required: As determined by the Objective Manager. Initiated by David P. Harrison.

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
03/27/2020	04	Revision initiated to incorporate relevant information from ORAUT-PROC-0060 Rev. 01. Rewritten such that only a best-estimate approach is used in determining the environmental doses. Radon-220 and ^{228}Ra intakes were added for years of thorium operations from 1963 to 1966. Table added (Table 4-1) for airborne concentrations, which feed the radionuclide intake tables (Tables 4-3 and 4-4). Intakes based on averages were converted to medians of a lognormal distribution using equations in Battelle-TIB-5000, resulting in an adjustment factor of 1.828. The following years, facilities, and nuclides were adjusted by dividing by 1.828 as they were not adjusted in Rev 03: WSRP U-234: 1990–2001; WSRP Radon: 1983–2001; WSP U-234: 1985–2001; WSP Th-230: 1985–2001; WSP Radon: 1985–2001; WSQ Radon: 1983–2001. WSQ U-234 values for the years 1990, 1991, 1993–1996, and 1998–2001 were changed. Rev 03 set these values equal to 0 as the airborne concentrations were considered to be insignificant. However, the nonzero airborne U-234 concentrations were included in this revision. The airborne concentration values for 1992 and 1997 were equal to zero thus they were not changed. The RU contaminant intakes from 1988 to 2001 were changed as the uranium intakes for those years were decreased by a factor of 1.828 from converting from an arithmetic mean or average to a median of a lognormal distribution. Intakes were converted to units of activity per calendar day by dividing by an average of 365.25 days per calendar year. Maximum intakes for U and Rn added to Table 4-1. Incorporates formal internal and NIOSH review comments. Constitutes a total rewrite of the document. Training required: As determined by the Objective Manager. Initiated by David P. Harrison.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS AND ABBREVIATIONS

AEC	U.S. Atomic Energy Commission
AMAD	activity median aerodynamic diameter
AWE	atomic weapons employer
Bq	becquerel
Ci	curie
cm	centimeter
d	day
DCAS	Division of Compensation Analysis and Support
DCF	dose conversion factor
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOL	U.S. Department of Labor
DR	dose reconstructor
EEOICPA	Energy Employees Occupational Illness Compensation Program Act of 2000
EU	enriched uranium
ft	feet
GSD	geometric standard deviation
hr	hour
IREP	Interactive RadioEpidemiological Program
L	liter
m	meter
mg	milligram
mrem	millirem
NIOSH	National Institute for Occupational Safety and Health
NU	natural uranium
ORAU	Oak Ridge Associated Universities
pCi	picocurie
ppb	parts per billion
RU	recycled uranium
s	second
SEC	Special Exposure Cohort
SRDB Ref ID	Site Research Database Reference Identification (number)
TBD	technical basis document
U.S.C.	United States Code

WLM	working level month
WSCP	Weldon Spring Chemical Plant
WSP	Weldon Spring Plant (also used where it is unnecessary to distinguish between the Weldon Spring Plant, Weldon Spring Quarry, and Weldon Spring Raffinate Pits)
WSQ	Weldon Spring Quarry
WSRP	Weldon Spring Raffinate Pits
yr	year
µCi	microcurie
µm	micrometer
µR	microroentgen
§	section or sections

4.1 INTRODUCTION

Technical basis documents (TBDs) 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 historical background information and guidance to assist in the preparation of dose reconstructions at particular U.S. Department of Energy (DOE) or Atomic Weapons Employer (AWE) facilities or categories of DOE or AWE facilities. They will be revised in the event additional relevant information is obtained about the affected DOE or AWE facility(ies), such as changing scientific understanding of operations, processes, or procedures involving radioactive materials. These documents may be used to assist NIOSH staff in the evaluation of Special Exposure Cohort (SEC) petitions and the completion of individual dose reconstructions under Part B of the Energy Employees Occupational Illness Compensation Program Act of 2000 (EEOICPA).

In this document the word “facility” is used to refer to an area, building, or group of buildings that served a specific purpose at a DOE or AWE facility. It does not mean nor should it be equated to an “AWE facility” or a “DOE facility.” The term “AWE facility” is defined in EEOICPA to mean “a facility, owned by an atomic weapons employer, that is or was used to process or produce, for use by the United States, material that emitted radiation and was used in the production of an atomic weapon, excluding uranium mining or milling” [42 *United States Code* (USC) 7384l(5)]. On the other hand, a DOE facility is defined as “any building, structure, or premise, including the grounds upon which such building, structure, or premise is located—(A) in which operations are, or have been, conducted by, or on behalf of, the [DOE] (except for buildings, structures, premises, grounds, or operations … pertaining to the Naval Nuclear Propulsion Program); and (B) with regard to which the [DOE] has or had—(i) a proprietary interest; or (ii) entered into a contract with an entity to provide management and operation, management and integration, environmental remediation services, construction, or maintenance services” [42 USC 7384l(12)]. The DOE determines whether a site meets the statutory definition of an AWE facility and the U.S. Department of Labor (DOL) determines if a site is a DOE facility and, if it is, designates it as such.

Under EEOICPA, a Part B cancer claim for benefits must be based on an energy employee’s eligible employment and occupational radiation exposure at a DOE or AWE facility during the facility’s designated time period and location (i.e., a “covered employee with cancer”). After DOL determines that a claim meets the eligibility requirements under Part B of EEOICPA, DOL transmits the claim to NIOSH for a dose reconstruction. EEOICPA provides, among other things, guidance on eligible employment and the types of radiation exposure to be included in an individual dose reconstruction. Under EEOICPA, eligible employment at a DOE facility includes individuals who are or were employed by DOE and its predecessor agencies, as well as their contractors and subcontractors at the facility [42 USC 7384l(11)]. Also under EEOICPA, the types of exposure to be included in dose reconstructions for DOE employees are those radiation exposures incurred in the performance of duty. As such, NIOSH includes all radiation exposures received as a condition of employment at DOE facilities in its dose reconstructions for covered employees, which may include radiation exposures related to the Naval Nuclear Propulsion Program at DOE facilities, if applicable. This is because NIOSH does not determine the fraction of total measured radiation exposure at a DOE facility that is contributed by the Naval Nuclear Propulsion Program at the DOE facility during a specified period of time for inclusion in dose reconstruction.

NIOSH does not consider the following types of exposure as those incurred in the performance of duty as a condition of employment at a DOE facility. Therefore these exposures are not included in dose reconstructions for covered employees [NIOSH 2010]:

- Background radiation, including radiation from naturally occurring radon present in conventional structures, and
- Radiation from X-rays received in the diagnosis of injuries or illnesses or for therapeutic reasons.

4.1.1 Purpose

The purpose of this technical basis document (TBD) is to describe the potential occupational environmental dose to workers at the Weldon Spring Plant (WSP), Weldon Spring Raffinate Pits (WSRP), and the Weldon Spring Quarry (WSQ). Occupational environmental exposure refers to exposures workers might have received while on the site but outside the facilities from elevated ambient radiation, facility effluent releases to the environment, and resuspension of radionuclides in soils. Effluent releases can result in internal and external exposures by inhalation of airborne radionuclides and by submersion in an effluent. This TBD provides estimated annual intakes for inhalation exposure and estimated doses from submersion and ambient exposure at WSP.

4.1.2 Scope

Historically, the WSP has been called the Weldon Spring Site, Weldon Spring Chemical Plant (WSCP), and the Weldon Spring Feed Materials Plant. The WSP is also known as the Chemical Plant, Main Plant, or Main Site. The facilities covered under EEOICPA are the WSP, WSQ, and the WSRP. For convenience, WSP is used throughout the remainder of this document where it is unnecessary to distinguish between the plant, the quarry, and the raffinate pits.

There are four periods for WSP:

- Site acquisition and development, 1954 to 1957;
- Operational, 1957 to 1966;
- U.S. Department of Defense (DOD) control of the WSP, 1967 to 1985; and
- Remediation, 1985 to 2002.

WSP employment is covered under EEOICPA only during the operational and remediation periods when the U.S. Atomic Energy Commission (AEC), U.S. Energy Research and Development Administration, and DOE had contractors and radioactive materials at WSP. WSQ and WSRP employment is covered during those periods and during the DOD control period. Due to the nature of site activities and available data, this document refers to the combined DOD control and remediation periods as the "postoperational years." The Weldon Spring Site Remediation Program was effectively complete in 2002. A formal review of the remedial action has found that the remedies are "protective of human health and the environment" (DOE 2006). Therefore, all environmental doses in 2002 are zero. The site has since been transferred for long-term surveillance and maintenance, and it is not covered under EEOICPA beyond 2002.

Workers at WSP received environmental doses during the operational period from stack effluents from buildings, contamination of soil from deposition of stack releases, and onsite storage of ore concentrates. Workers at WSQ received environmental doses during the same period from resuspension from contaminated rubble and soil being placed in (or already in) the disposal area. During the remediation period, workers received occupational doses from contaminated soils and structures at WSQ, WSP, and WSRP during excavation of contaminated sludges and soils, demolition and removal of contaminated structures, and placement of contaminated media in the onsite disposal facility in WSRP. For more information, see ORAUT-TKBS-0028-2, *Weldon Spring Plant – Site Description* (ORAUT 2017a).

Section 4.2 contains information for estimation of internal environmental dose and includes discussions of airborne particulate and radon concentrations at WSP, WSRP, and WSQ. Section 4.3 contains information for estimation of external environmental dose. Section 4.4 discusses the uncertainties that apply to the environmental doses. Section 4.5 summarizes the tables that provide environmental dose default values for use by dose reconstructors (DRs). Attributions and

annotations, indicated by bracketed callouts and used to identify the source, justification, or clarification of the associated information, are presented in Section 4.6.

4.2 INTERNAL DOSE FROM ONSITE ATMOSPHERIC RADIONUCLIDE CONCENTRATIONS

This section describes internal exposure from the intake of radionuclides. Section 4.2.1 identifies the radionuclides of concern. Section 4.2.2 describes specific sources of various radionuclides in the outdoor environment. Section 4.2.3 presents the methods that were used to calculate activity intakes of radioactivity in the form of air particulates and radon. Section 4.5 provides tabulated values for maximum sitewide median inhalation intakes of radioactive air particulates and radon at WSP, WSRP, and WSQ.

4.2.1 Radionuclides of Concern

The radionuclides of concern are defined as those that make up 95% of the potential internal dose. For the purposes of dose reconstruction, the assumption was made that all uranium processed at WSP was natural uranium (NU) from 1957 through 1962, with a specific activity of 683 pCi/mg. After 1962, all uranium was assumed to be enriched to 1%, with a specific activity of 973 pCi/mg (ORAUT 2017b).

4.2.1.1 Airborne Particulate Radionuclides

The radionuclides of concern for dose reconstruction are the naturally occurring isotopes of uranium (^{234}U, ^{235}U, and ^{238}U), their decay products (primarily ^{230}Th and ^{226}Ra), isotopes of natural thorium (^{228}Th and ^{232}Th), and their decay products. ORAUT-TKBS-0028-5, *Weldon Spring Plant – Occupational Internal Dose* (ORAUT 2017b) provides additional details for the internal deposition of these radionuclides of concern.

4.2.1.2 Radon

Three radon isotopes are generated during the decay of ^{235}U, ^{238}U, and ^{232}Th: ^{219}Rn, ^{222}Rn, and ^{220}Rn, respectively. Due to the limited amount of enriched uranium (up to 1%) processed at WSP, there was no large source of ^{223}Ra and in turn ^{219}Rn at WSP. The risks associated with ^{219}Rn, due to its extremely short half-life (4 seconds) and small source term, were insignificant. Therefore, this TBD considers only the inhalation intakes for ^{222}Rn and ^{220}Rn to be potentially significant, as discussed in more detail below.

4.2.1.3 Recycled Uranium

The DR should assume, as favorable to claimants, that all of the uranium WSP processed beginning in 1961 was recycled uranium (RU) (ORAUT 2017b). For the periods that include RU (i.e., after 1960), the DR should refer to Section 5.6.1.3.3 of ORAUT-TKBS-0028-5, *Weldon Spring Plant – Occupational Internal Dose* (ORAUT 2017b), in relation to RU contaminant mass concentrations.

4.2.2 Source Terms for Airborne Radionuclides

4.2.2.1 Operational Period, 1957 to 1966

WSP

Uranium and thorium were released from the WSP process building stacks during the operational period. No stack monitoring data have been found. Perimeter monitoring data are available in WSP environmental reports and a materials balance study (Harris 1986, pp. 10, 33) and form the basis of the estimates of uranium and thorium intake rates. The reported atmospheric discharges from the materials balance study were engineering estimates that were derived from airflows and other

process factors (ORAUT 2017a). The estimated amount of uranium activity that was emitted from the operating plants ranged from approximately 1 to 5 Ci/yr.

An estimate of radon release based on the amount of processed uranium during the operational period ranged from 12 to 34 Ci/yr assuming (1) 5,000 to 14,500 metric tons of uranium materials were processed per year, (2) 70% of this was elemental uranium, (3) radium activity was 1% of the uranium activity (believed to be conservatively high considering the radium content in yellowcake), (4) radon was in equilibrium with radium, and (5) all radon was released through the stack during processing (Meshkov et al. 1986, pp. 47–48).

No raw ores were processed at WSP. Only ore concentrates (e.g., yellowcake) and other highly refined uranium and thorium compounds were processed. The ore concentrates were a relatively small source of radon because most of the radium (the radon precursor in the ore) was removed in the milling process, which occurred elsewhere.

According to the review of source emissions by Meshkov et al. (1986), only a fraction of radon (about 20%) is released when attached to solid particles, such as those that occur in uranium ore concentrates. However, the digestion phase of the refining process would have released the trapped radon during the operational period. Off-gases that contained radon isotopes from this process were conveyed to the acid recovery plant at WSP. The discharge from the acid recovery plant was the primary source of radon emission (Meshkov et al. 1986).

Drums of yellowcake were emptied into the hopper at the top of the receiving and sampling building (ORAUT 2017a). Dust was collected in three large collectors, each with its own stack, and either repackaged and shipped off the site or reprocessed. In the refinery plant process, uranium-laden dust was generated during material transfers, denitration, reduction and hydrofluorination, and conversion to solid metal. The denitration process was the dustiest part of the operation. Therefore, point sources of uranium emissions from stacks existed during this period. Stack monitoring concentration data for the operational period are not available.

Meshkov et al. (1986, p. 47) and Sears et al. (1975, p. 143) assumed that activity concentrations of ^{230}Th, ^{226}Ra, and ^{210}Pb in uranium ore concentrates were 5%, 1%, and 1%, respectively, of that of ^{238}U. However, specific isotopic characterization of raffinates at WSP indicates that the uranium mill processes that produced the yellowcake concentrates for both Feed Materials Production Center and WSP effectively removed the radium but were not effective in removing thorium, specifically ^{230}Th (Sears 1976, p. 4; ORAUT 2017c, p. 31). Therefore, this TBD assumes activity ratios for ^{230}Th, ^{226}Ra, and ^{210}Pb in uranium ore concentrate of 80%, 1%, and 1%, respectively, of that of ^{238}U (Mason 1958; ORAUT 2017c).

WSRP

Impurities that were generated in the uranyl nitrate purification process were bled off in the raffinate, which was also pumped to WSRP. The raffinate contained a variety of radionuclides including thorium and radium (Author unknown, 1967, pp. 10–11). Wastes in WSRP were not a significant source of particulate or gaseous airborne radionuclides during the operational period due primarily to the presence of water in the pits. It is unlikely that a significant portion of the sediments became sufficiently dry to be considered a source term during this period, even though 2 decades later DOE (1984a, p. 14) reported that Pits 1 and 2 could become dry during the summer months. National Lead Company of Ohio (NLO 1977, p. 18) stated:

> *The transport of radiological contamination by air is not considered a problem at the site. Good ground cover exists and the raffinate pits are either covered with water or remain moist due to the balance between precipitation and evaporation in the area. Even in*

times of prolonged dry weather, the inherent consistency of the raffinate material contained in the pits precludes drying.

If the raffinate pits had been dry, resuspension from the pits should be reflected in the boundary station air sampling results (NIOSH 2012a). As discussed below in Section 4.2.3.1, perimeter monitoring data were extrapolated to the central portion of the plant for use in occupational environmental intake rate calculation.

WSQ

Wastes that were disposed of in WSQ during the operational period presented a diffuse source of particulate emissions to the air as a result of entrainment of contaminated, wind-exposed surface soil or rubble. Radon-222 and ^{220}Rn (from ^{226}Ra and ^{224}Ra, respectively) in the quarry also presented a diffuse source of airborne radionuclides. Before 1963, the quarry contained only drummed thorium wastes that were probably submerged (Author unknown 1967, pp. 17–19) and not a significant source of radon because water is an effective barrier to radon release. Each 25-cm increase in the depth of a water column reduces the ^{222}Rn concentration by approximately 50% (Usman, Spitz, and Weisman 2005). The attenuation of ^{220}Rn flux is expected to be even larger due to the shorter half-life of ^{220}Rn. Therefore, the radon release before 1963 was negligibly small.

In 1963 and 1964, an estimated 38,000 m^3 of uranium- and radium-contaminated rubble, equipment, and soil were placed in WSQ after demolition of the Mallinckrodt Destrehan Street site. A majority of this waste was not submerged and was a potential source of radon exposure (Author unknown 1967, pp. 17–20). The emission rate from the quarry is assumed to be the same from 1963 until it was measured during the postoperational years.

4.2.2.2 Postoperational Years, 1967 to 2002

Diffuse (i.e., non-point-source) emissions predominated as the source of radionuclides in the air at the WSP, WSRP, and WSQ. Annual environmental monitoring reports provided estimates of air concentrations of particulate radionuclides and of radon at WSP and WSQ beginning in 1979. These estimates reflect emissions during the later years (1975 to 1985) of the DOD control period and throughout the remediation period (1985 to 2002).

4.2.3 Annual Intake of Radionuclides

Descriptions of particle size and absorption type are not available for radionuclides of concern. DRs should assume the default aerosol size of 5-µm activity median aerodynamic diameter (AMAD) (ICRP 1994; ORAUT 2018a). In addition, DRs should select the absorption type that yields the highest dose to the organ of interest. Calculated intakes in units of activity per calendar day (becquerel per day, Bq/d) are based on a 2,400-m^3/yr inhalation rate using a breathing rate of 1.2 m^3/hr for light activity (Section 9.3.1.1 of ICRP 1994) and a 2,000-hour work year, adjusting for an average of 365.25 days in a calendar year (ORAUT 2020). Intakes can be scaled to a different rate or to consider partial year exposures. Environmental intakes from ingestion are considered negligibly small and therefore have not been included in the tabulated results. Airborne radioactivity concentrations that were reported as an arithmetic mean were converted to a median of a lognormal distribution using the equations in Table 2.2 of the Battelle-TIB-5000 (BT 2007), and a geometric standard deviation of 3 (ORAUT 2018a, p. 14; ORAUT 2012, p. 17).

4.2.3.1 Operational Period, 1957 to 1966

This TBD analysis used the available perimeter monitoring data to calculate estimated intakes of radioactive airborne particulates and radon according to the methods described in this section.

Airborne Particulate Radionuclides

Uranium air concentration measurements at the WSP (and WSRP) perimeter from 1959 through 1965 were evaluated. The perimeter data were converted to units of becquerels per cubic meter and adjusted by the dilution factor of 30 (discussed below), and the median airborne particulate concentrations are presented in Table 4-1. The original data were reported in units of "special uranium microcuries," which is a modification of the "special curie" as defined in DOE (2009) and stated in the glossary section of this TBD. Converting to units of becquerel, the special uranium microcurie is multiplied by 3.7×10^4 Bq/µCi and by a factor of 2.024 to report total uranium activity. Refer to ORAUT-TKBS-0028-5 (ORAUT 2017b) for an expanded discussion of the use of the special uranium microcurie at WSP. Other radionuclides were not measured.

Table 4-1. Median airborne radioactivity concentrations (WSP, WSRP, WSQ) and sitewide maximums (U and Rn).[a]

Year	WSRP U-234 (Bq/m^3)	WSRP Radon (Bq/m^3)	WSP U-234 (Bq/m^3)	WSP Th-230 (Bq/m^3)	WSP natural Thorium (Bq/m^3)	WSP Radon (Bq/m^3)	WSQ U-234 (Bq/m^3)	WSQ Radon (Bq/m^3)	Max. U-234 (Bq/m^3)	Max. Radon (Bq/m^3)
1957–1959	0.00E+00	0.00E+00	2.83E–01	2.26E–01	0.00E+00	(b)	0.00E+00	0.00E+00	2.83E–01	(b)
1960	0.00E+00	0.00E+00	5.77E–01	4.61E–01	0.00E+00	(b)	0.00E+00	0.00E+00	5.77E–01	(b)
1961	0.00E+00	0.00E+00	9.90E–01	7.92E–01	0.00E+00	(b)	1.45E–03	0.00E+00	9.90E–01	(b)
1962	0.00E+00	0.00E+00	2.44E–01	1.95E–01	0.00E+00	(b)	9.83E–04	0.00E+00	2.44E–01	(b)
1963	0.00E+00	0.00E+00	4.42E–01	3.54E–01	0.00E+00	(b)	1.06E–03	(b)	4.42E–01	(b)
1964	0.00E+00	0.00E+00	3.38E–01	2.70E–01	2.62E–04	(b)	2.46E–03	(b)	3.38E–01	(b)
1965	0.00E+00	0.00E+00	1.84E–01	1.47E–01	4.86E–03	(b)	1.64E–02	(b)	1.84E–01	(b)
1966	0.00E+00	0.00E+00	1.84E–01	1.47E–01	1.59E–02	(b)	1.64E–02	(b)	1.84E–01	(b)
1967–1974	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1975–1976	0.00E+00	4.26E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.64E–02	1.99E+01	1.64E–02	4.26E+01
1977–1978	0.00E+00	6.07E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.64E–02	2.02E+01	1.64E–02	6.07E+01
1979	0.00E+00	1.11E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.64E–02	1.11E+01	1.64E–02	1.11E+01
1980	0.00E+00	6.88E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.64E–02	1.82E+01	1.64E–02	6.88E+01
1981	0.00E+00	4.51E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.64E–02	2.33E+01	1.64E–02	4.51E+01
1982	0.00E+00	9.11E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.64E–02	2.65E+01	1.64E–02	2.65E+01
1983	0.00E+00	5.74E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.64E–02	1.20E+01	1.64E–02	1.20E+01
1984	0.00E+00	9.84E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.64E–02	1.37E+01	1.64E–02	1.37E+01
1985	0.00E+00	6.56E+00	7.47E–04	5.97E–04	0.00E+00	1.23E+02	1.64E–02	1.37E+01	1.64E–02	1.23E+02
1986	0.00E+00	9.30E+00	7.47E–04	5.97E–04	0.00E+00	1.89E+02	1.64E–02	1.31E+01	1.64E–02	1.89E+02
1987	0.00E+00	7.66E+00	7.47E–04	5.97E–04	0.00E+00	2.46E+02	1.64E–02	2.46E+01	1.64E–02	2.46E+02
1988	0.00E+00	1.20E+01	7.47E–04	5.97E–04	0.00E+00	3.36E+02	0.00E+00	3.72E+01	7.47E–04	3.36E+02
1989	0.00E+00	9.02E+00	7.47E–04	5.97E–04	0.00E+00	3.12E+02	0.00E+00	2.35E+01	7.47E–04	3.12E+02
1990	2.73E–05	5.47E+00	7.47E–04	5.97E–04	0.00E+00	1.97E+02	9.30E–06	1.91E+01	7.47E–04	1.97E+02
1991	1.37E–05	6.02E+00	4.51E–04	3.61E–04	0.00E+00	1.64E+02	1.80E–06	1.64E+01	4.51E–04	1.64E+02
1992	1.07E–05	6.02E+00	3.36E–04	2.69E–04	0.00E+00	1.31E+02	0.00E+00	1.48E+01	3.36E–04	1.31E+02
1993	1.26E–05	2.73E+00	3.77E–04	3.02E–04	0.00E+00	6.07E+01	1.70E–06	3.34E+01	3.77E–04	6.07E+01
1994	1.48E–05	7.66E+00	5.17E–04	4.13E–04	0.00E+00	1.39E+02	1.31E–05	9.30E+01	5.17E–04	1.39E+02
1995	1.29E–05	9.30E+00	4.18E–04	3.35E–04	0.00E+00	1.80E+02	4.38E–06	3.17E+01	4.18E–04	1.80E+02
1996	1.70E–05	1.56E+01	4.84E–04	3.87E–04	0.00E+00	2.21E+02	1.80E–06	7.11E+00	4.84E–04	2.21E+02
1997	2.05E–05	3.55E+01	4.51E–04	3.61E–04	0.00E+00	1.80E+02	0.00E+00	6.02E+00	4.51E–04	1.80E+02
1998	2.38E–05	6.29E+00	6.32E–04	5.05E–04	0.00E+00	1.07E+02	1.42E–06	4.05E+00	6.32E–04	1.07E+02
1999	2.11E–05	1.01E+01	6.23E–04	4.99E–04	0.00E+00	2.05E+02	2.02E–07	9.30E+00	6.23E–04	2.05E+02
2000	1.12E–05	5.47E+00	4.18E–04	3.35E–04	0.00E+00	2.13E+02	1.80E–06	7.11E+00	4.18E–04	2.13E+02
2001	1.12E–05	5.47E+00	4.18E–04	3.35E–04	0.00E+00	2.13E+02	1.80E–06	7.11E+00	4.18E–04	2.13E+02
2002	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

a Source: ORAUT (2019b).

b Radon concentrations were calculated for the WSP during the operational period and for the WSQ from 1963 through 1966. However, these concentrations were not used in determining the radon intake for the operational period. The value of 12.4 WLM/yr (or 3.39E-02 WLM/d) was used from ORAUT (2017b, p. 44) as stated below in Table 4-3.

Perimeter monitoring data were extrapolated to the central portion of the plant for use in occupational environmental intake rate calculation. The extrapolation was based on the ratio of the calculated ground-level air concentration at two different locations of interest (100 meters and 750 meters discussed further below). The ground-level air concentrations were calculated at these two downwind

distances using the Pasquill-Gifford equation for Gaussian plume atmospheric dispersion (shown below) assuming an emission rate of 1 Bq/s and the following parameters:

$$\frac{\chi(x,y)}{Q} = \frac{1}{2\pi\sigma_y\sigma_z u}\exp\left[-\frac{1}{2}\left(\frac{y^2}{\sigma_z^2}+\frac{H^2}{\sigma_z^2}\right)\right] \quad (4\text{-}1)$$

where

$\chi(x,y)$ = ground-level concentration at point (x,y) (Bq/m^3).

x = downwind distance on plume centerline (m). In this case the values were 100 m and 750 m.

y = crosswind distance (m). In this case, y = 0 m.

Q = emission rate (Bq/s), which is set to unity in this case.

σ_y, σ_z = horizontal and vertical standard deviations of the contaminant concentration in the plume (m). At 100 m, σ_y = 17.6 and σ_z = 10.9. At 750 m, σ_y = 109 and σ_z = 80.

u = mean wind speed at level of plume centerline (m/s), which in this case is an annual average of 4.6 m/s.

H = effective release height (m), which is assumed to be 10 m to represent the stack of a large one-story industrial building.

The values of σ_y and σ_z were determined from equations the U.S. Nuclear Regulatory Commission uses in the RACHET2 computer program (Napier and Ramsdell 2005).

The wind speed of 4.6 m/s was based on the average wind frequency data from Lambert Field in St. Louis for 1961 through 1990 (ISCO 2009). The Lambert Field wind speed data were used since it is likely that it is the closest facility to the Weldon Spring Plant to which reliable wind speed information could be obtained. The same data were used to select an atmospheric stability class. Stability class B was selected for this analysis to represent a relatively turbulent flow that would increase the dilution between the center of the plant and the plant perimeter where the measurements were made. Stability class B is characterized as an unstable or turbulent atmosphere with surface wind speed in the range of 3 to 5 m/s and moderate incoming solar radiation. The only stability class that would be more turbulent – and therefore more favorable to the claimant – would be class A, but the wind frequency data do not support that choice.

The distances for the location of the perimeter monitoring and the onsite worker were based on inspection of a map of WSP sampling locations near the fence line (see Figure 4-1). Figure 4-1 does not include a distance scale, but Figure 4-2 includes a distance scale and a circle superimposed near the fence line. The radius of the circle is nominally 600 m, so this value was considered to represent the distance from the release point to the sampling location.

Further inspection shows that the processing area is on the east side of the plant, and a better representation of the greatest distance from the center of the processing area to a point on the perimeter is 750 m. The value of 100 m for the exposed worker location is based on the limitations of the atmospheric dispersion model and is because it is likely to be a reasonable average estimate of the distance of any individual on the ground from a stack on the roof of a process building.

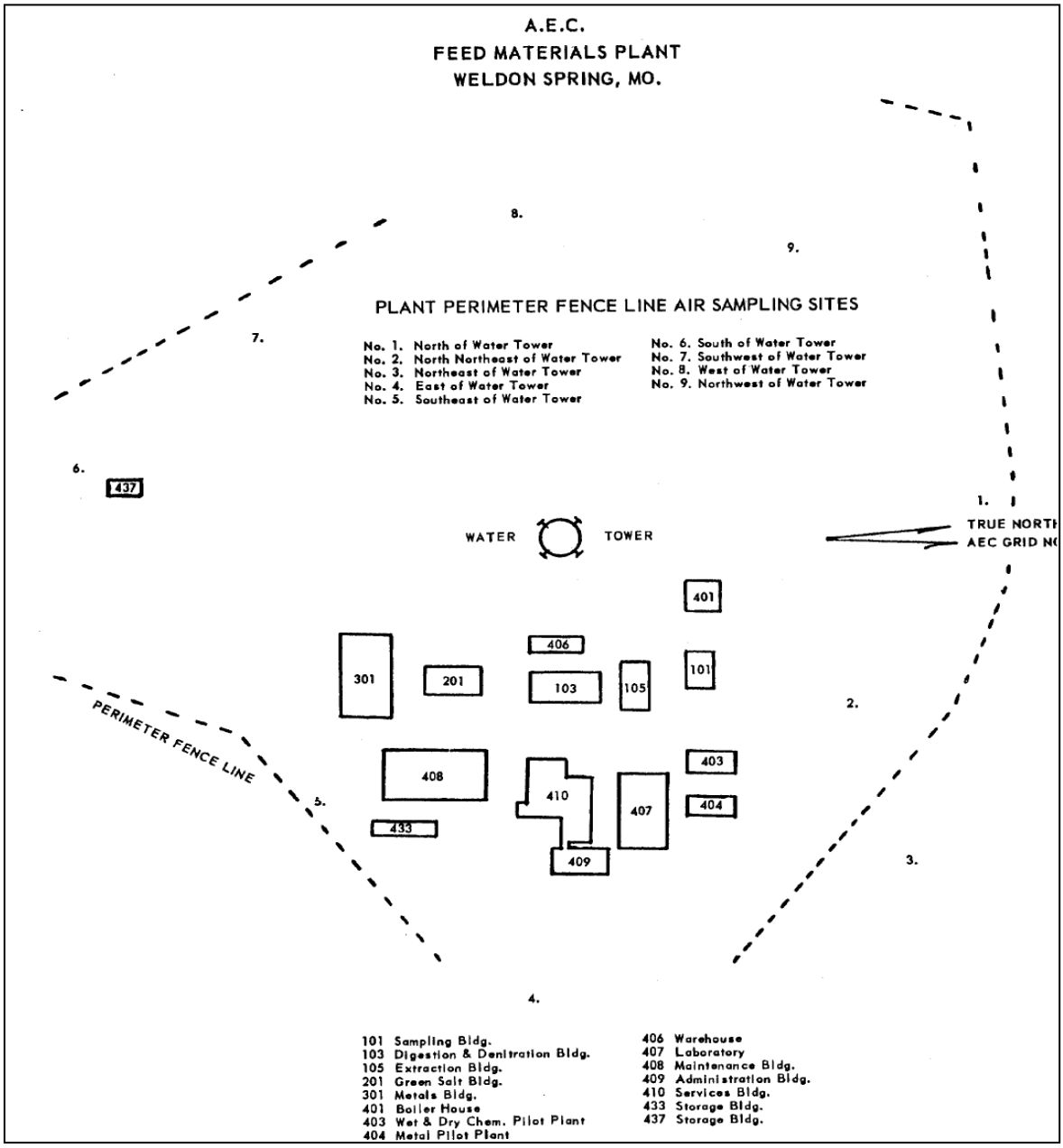

Figure 4-1. Perimeter sampling locations and processing facilities (lacking distance scale) (Meshkov et al. 1986, p. 123).

When Equation 4-1 is solved for the ground-level air concentration (i.e., a unit emission rate) at both 100 m and 750 m, the ratio of results defines a dilution factor that can be used to extrapolate the data that were measured at the perimeter to the concentration outdoors in the processing area. The calculated dilution factor is 30. For example, a measured air concentration of 0.01 Bq/m^3 at the perimeter can be extrapolated to a concentration of 0.3 Bq/m^3 near the center of the operating area of the plant.

Thorium intake (natural thorium or ^{232}Th), for those years when it was processed (1963 to 1966), can be estimated by scaling the annual uranium and thorium mass throughput rates (2017a, p. 11) and apportioning that fraction of the intake rate to thorium instead of uranium. This is justified by the fact that similar or identical processing facilities and environmental controls were used for both uranium and thorium operations, so a portion of the environmental release could be expected to be thorium.

Thorium-228 is assumed to be in equilibrium with ^{232}Th, so the ^{228}Th intakes and activities equal those for ^{232}Th. Radium-228 is added at a ratio of 1-to-2 ^{232}Th-to-^{228}Ra (NIOSH 2010b, p. 57).

The measured perimeter air concentration data for WSP and WSQ can be found in quarterly and semiannual environmental monitoring reports (MCW 1961a, p. 36, 53–54; 1961b, p. 6; 1961c, pp. 9, 11; 1962a, p. 14; 1962b, p. 44, p. 65; 1962c, pp. 85–86; 1964a, p. 14; 1964b, pp. 10–11; 1965, pp. 13–14; 1966, pp. 10–11), and in the summary report by Meshkov et al. (1986, pp. 101, 103–104). In some instances, the same data were reported in more than one document; in those cases the contemporary environmental reports were preferred as the primary data source. Daily intake rates can be calculated based on the extrapolated air concentrations and an assumed breathing rate of 1.2 m^3/hr for 2,000 hr/yr (Section 9.3.1.1 of ICRP 1994), adjusted for an average of 365.25 days in a calendar year (ORAUT 2020).

For 1957 and 1958 at WSP, for which measurements are not available, this analysis assumed that perimeter air concentrations were the same as the measured concentrations in 1959, which is the operational year with the highest measured perimeter concentrations. This is considered an overestimate for the first 2 years when uranium receipts were lower than those during the main production years (1960 to 1964; see ORAUT 2017a).

Radon

Measured ground-level air concentrations of radon during the operational period were not reported in the available references, but Meshkov et al. (1986) estimated an annual release rate of ^{222}Rn in the range of 12 to 34 Ci. This radon was released from the acid recovery building stack. Using the radon intake calculation as stated in ORAUT-TKBS-0028-5 (ORAUT 2017b), a daily ^{222}Rn intake of 3.39E-02 working level months/day (WLM/d), or 12.4 WLM/yr and adjusting for 365.25 days in a calendar year, should be assigned to WSP personnel during the operational period (NIOSH 2012b, pp. 112–116). This TBD analysis estimated radon concentrations for the WSQ during the operational period from measurements in the vicinity from 1977 through 1982 (Weidner and Boback 1982, p. 50; Bechtel 1983a, p. 25; 1983b, pp. 24, 27; Meshkov et al. 1986, p. 101). This approach is justified because the activities of ^{226}Ra and ^{224}Ra were not significantly depleted in the quarry over time due to limited leaching and continuous production of these isotopes from precursors in the waste. These years reasonably represent radon emanations for the WSQ during the operational period. These measurements were applied only to the period from 1963 to 1966. Before that, drummed thorium waste was most likely submerged and no significant source of radon existed. There were no radon intakes assigned for the WSRP during the operational period since the source term was small and the contents of the pits were covered with water.

Thoron

Although the estimated dose attributable to ^{220}Rn and its progeny is relatively insignificant in relation to ^{222}Rn and its progeny because ^{222}Rn progeny have a higher estimated equilibrium factor and higher associated dose factors than the ^{220}Rn thoron progeny (DOE 2001a, pp. 31–35), an estimate of the ^{220}Rn release during the operational period was made. Natural thorium was processed on a batch basis in the refinery, and oxide production and firing systems at WSP from November 1963 through September 1966. Using the thoron intake calculation as stated in ORAUT-TKBS-0028-5 (ORAUT 2017b), a daily ^{220}Rn intake of 7.94E–06 WLM/d (2.9E–03 WLM/yr divided by 365.25 d/yr) should be assigned to WSP personnel from 1963 to 1966. This has been prorated for the partial years of thorium operations in 1963 and 1966 as shown in Tables 4-3 and 4-4. Similar to the rationale stated above, this thoron intake activity is applied to the WSQ as well. There were no thoron intakes assigned for the WSRP during the operational period since the source term was small and the contents of the pits were covered with water.

4.2.3.2 Postoperational Years, 1967 to 2002

DOE had no contractors on the site until 1975, when air monitoring occurred in the WSRP and WSQ areas. Measurements of radon in air appear in annual reports beginning with monitoring reports for 1979 and 1980 (Weidner and Boback 1982, pp. 28–30, 33, 50), which were specific to the raffinate pits and quarry. In October 1985, the radon monitoring program was expanded to include WSP (DOE 1986, pp. 34–35), which was transferred back to DOE at that time. Radioactive airborne particulates were not monitored before the beginning of remediation activities at the site in 1985. Air particulate monitoring was added beginning in 1987 at WSP and WSRP (DOE 1988, pp. 77–83) and beginning in 1989 at WSQ (DOE 1990a, pp. 125–133). Air sampling data from the annual monitoring reports from 1985 to 2000 (when remediation was nearly complete), were the basis for the following estimates of air concentrations and intakes at WSRP, WSP, and WSQ for periods after 1974.

4.2.3.2.1 Airborne Particulate Radionuclides

WSP
Airborne particulate results were reported at WSP beginning in 1987 (DOE 1988, pp. 77–83; 1989a, pp. 90–92; 1990a, pp. 125–133; 1991, pp. 131–135; 1992a, pp. 98–101; 1993, pp. 128–132; 1994, pp. 106–111; 1995, pp. 104–108; 1996, pp. 96–99; 1997, pp. 92–97; 1998a, pp. 78–81; 1999, pp. 86–90; 2000, pp. 81–85; 2001b, pp. 79–83). From 1987 to 1989, monitoring of particulates at a few perimeter locations for WSP indicated that measured gross alpha concentrations were statistically indistinguishable from background (DOE 1988, p. 81; 1989a, pp. 90–92; 1990a, pp. 125–133). Although a significant source term was not expected, the concentrations from 1985 to 1989 were set equal to the 1990 concentration value because it was the highest nonzero value for the adjacent year.

WSRP
Airborne particulate results were reported at WSRP beginning in 1987 (DOE 1988, pp. 77–83; 1989a, pp. 90–92; 1990a, pp. 125–133; 1991, pp. 131–135; 1992a, pp. 98–101; 1993, pp. 128–132; 1994, pp. 106–111; 1995, pp. 104–108; 1996, pp. 96–99; 1997, pp. 92–97; 1998a, pp. 78–81; 1999, pp. 86–90; 2000, pp. 81–85; 2001b, pp. 79–83). From 1987 to 1989, monitoring of particulates at a few perimeter locations for WSRP indicated that measured gross alpha concentrations were statistically indistinguishable from background (DOE 1988, p. 81; 1989a, pp. 90–92; 1990a, pp. 125–133). Therefore, the concentrations from 1987 to 1989 at WSRP are zero. Because all areas of WSRP were essentially undisturbed between 1975 and the beginning of remediation activities in 1985, and because no significant airborne concentration was likely because the source term was small and the contents of the pits were covered with water, this analysis assumed that radioactive airborne particulate concentrations before 1987 were the same as those measured in 1987 through 1989. Therefore, the particulate concentrations from 1975 through 1989 were zero.

WSQ
The airborne concentrations from 1975 to 1987 were set equal to the value for 1965 because there were no data for those years and the 1965 value is the closest measured year. Airborne particulate results were reported at WSQ beginning in 1988 (DOE 1988, pp. 77–83; 1989a, pp. 90–92; 1990a, pp. 125–133; 1991, pp. 131–135; 1992a, pp. 98–101; 1993, pp. 128–132; 1994, pp. 106–111; 1995, pp. 104–108; 1996, pp. 96–99; 1997, pp. 92–97; 1998a, pp. 78–81; 1999, pp. 86–90; 2000, pp. 81–85; 2001b, pp. 79–83). In 1988 and 1989 at WSQ, monitoring of particulates at a few perimeter locations indicated that measured gross alpha concentrations were statistically indistinguishable from background (DOE 1989a, p. 92; DOE 1990a, p. 133). Therefore, the concentrations in 1988 and 1989 at WSQ were assumed to be zero.

WSP, WSRP, and WSQ
From 1989 to 2000, concentrations of radioactive air particulates were measured and reported at the locations in Figures 4-3 and 4-4, even though many of the concentrations were statistically

indistinguishable from background. The measurements occurred at perimeter locations for WSP, WSRP, and WSQ. These perimeter data were extrapolated to represent concentrations at the center of the operating area using the method in Section 4.2.3.1. Therefore, the measured perimeter concentrations of airborne particulate radionuclides were multiplied by a factor of 30 to represent the average onsite airborne concentrations.

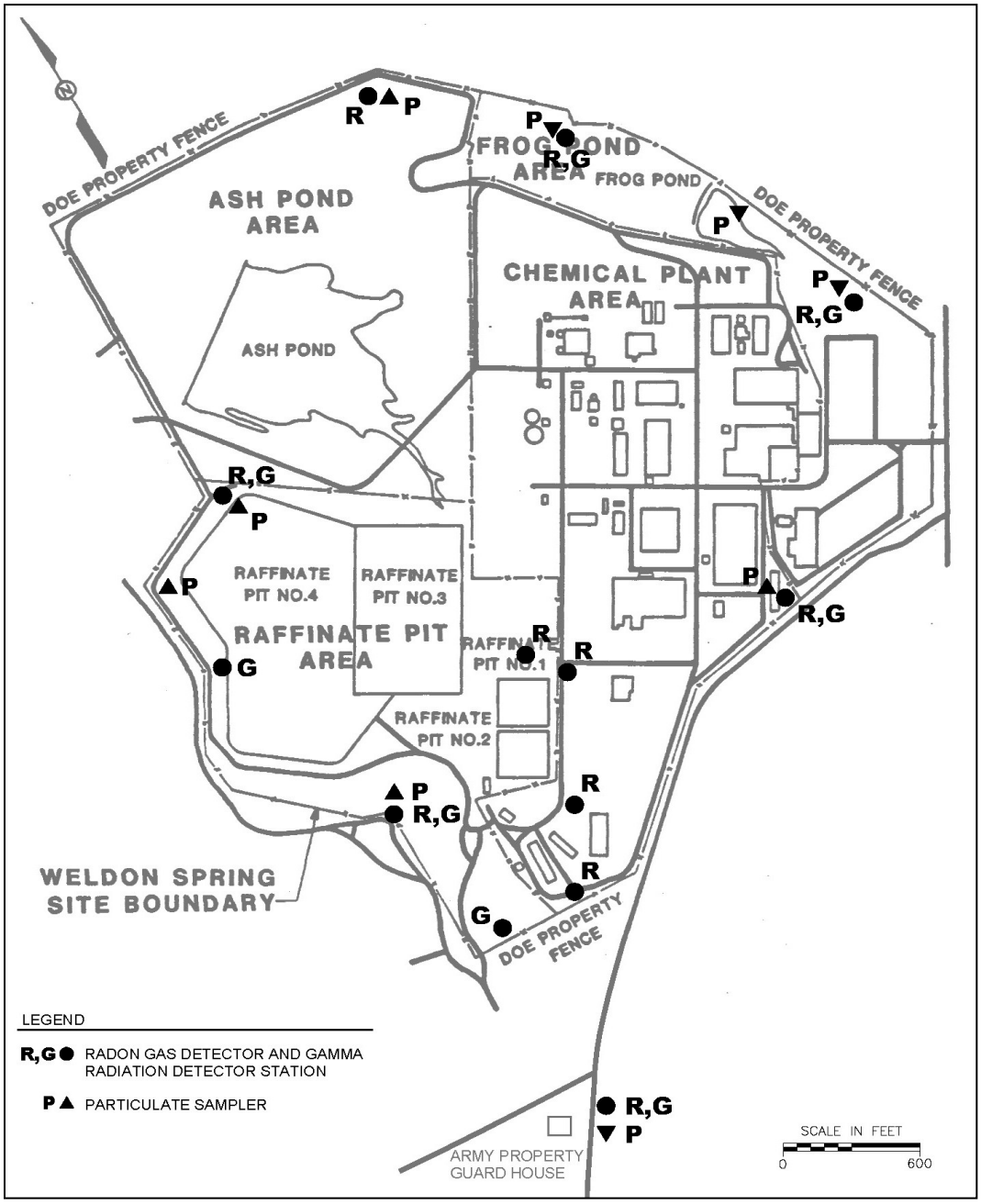

Figure 4-3. Air particulate (P), radon (R), and gamma (G) monitoring stations in WSP and WSRP (modified from DOE 1999, p. 69).

Section 4.2.1.1 identifies the radionuclides of concern as the naturally occurring isotopes of uranium (^{234}U, ^{235}U, and ^{238}U) and their decay products (primarily ^{230}Th and ^{226}Ra) as potentially significant isotopes of concern during the remediation period. However, air concentrations of these isotopes were measured in terms of gross alpha concentrations at WSP for most years of interest. The lack of refinement is probably because (1) the radionuclides of interest are alpha emitters and (2) the

perimeter data for WSP, WSRP, and WSQ, which are all that are available for air particulates, seldom showed air concentration measurements higher than those at offsite background monitoring stations.

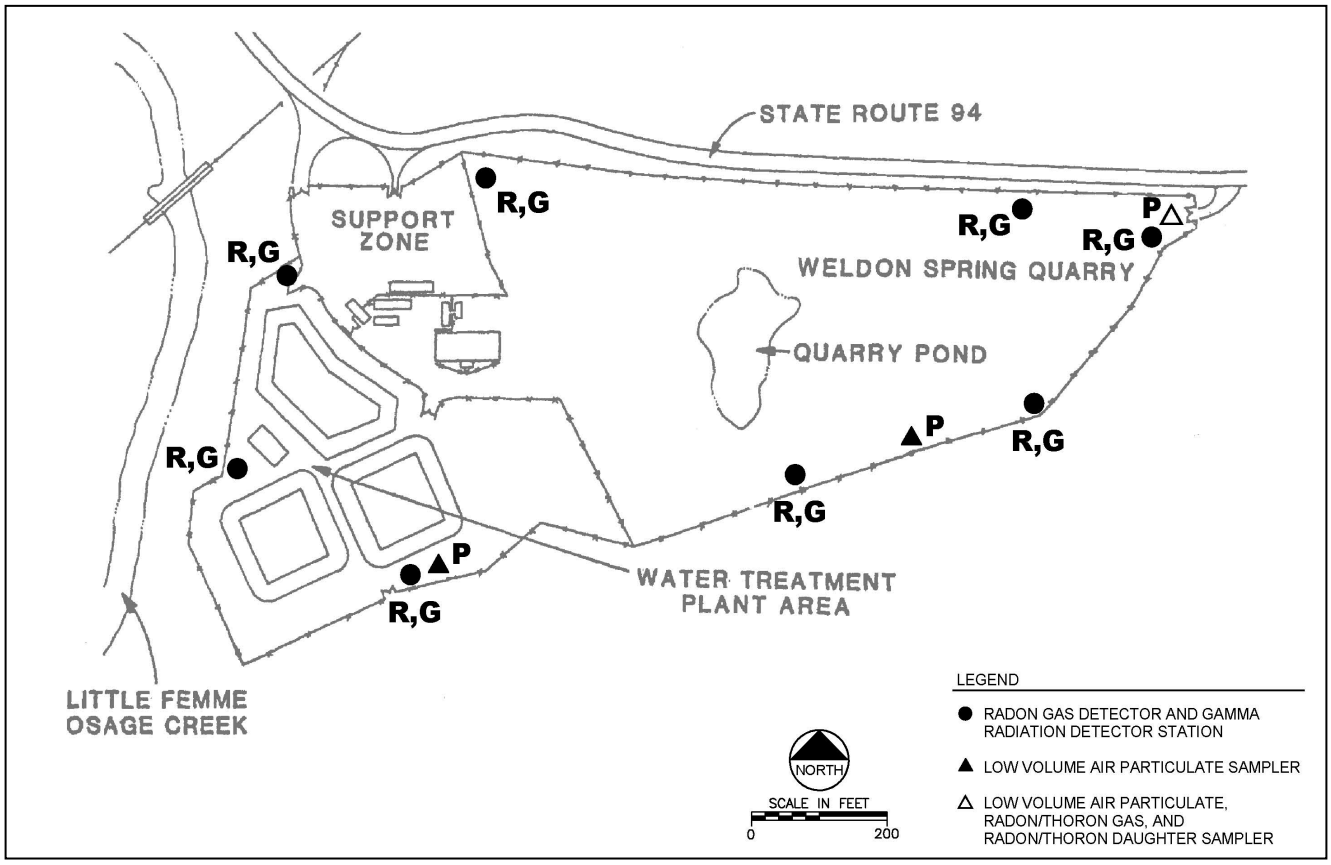

Figure 4-4. Air particulate (P), radon (R), and gamma (G) monitoring stations in WSQ (modified from DOE 1999, p. 70).

Air particulate monitoring ended at the end of 2000 for all WSP areas because radioactive waste handling activities were essentially complete and no critical receptor air monitoring data had demonstrated a dose to the public of greater than 1 mrem (DOE 2001b, pp. 95, 230–237; DOE 2003, pp. 33, 44). Because there was still some movement of material at the site and workplace monitors were used for the brief period of placement of waste material in the Disposal Cell in 2001 (DOE 2002, pp. 8–9), the intakes for 2001 were assumed to be equal to the intakes for 2000.

Table 4-2 lists RU contaminant intakes per unit activity of uranium. Table 4-3 lists the median intakes for WSP, WSRP, and WSQ, and Table 4-4 lists the maximum sitewide median ^{234}U intakes for the remediation period. These intakes correspond to the highest value, by year, for WSP, WSRP, and WSQ. The daily intakes were obtained by multiplying the ^{234}U concentrations (Bq/m^3) by an assumed inhalation rate of 2,400 m^3/yr (Section 9.3.1.1 of ICRP 1994), adjusted by dividing by an average of 365.25 day in a calendar year (ORAUT 2020). The RU contaminant intake activities were calculated as stated in Section 4.2.4 by multiplying the ratio stated in Table 4-2 by the ^{234}U value, either that stated in Table 4-3 or Table 4-4. As stated earlier, 232Th was estimated for 1964–1966 by scaling the annual uranium and thorium mass throughput rates and apportioning that fraction of the intake

rate to thorium. Thorium-228 and ^{228}Ra intake rates were included for those years at ratios stated earlier.

Table 4-2. RU contaminant intakes per unit activity of uranium, Bq/Bq U (ORAUT 2017c).

Radionuclide	1961–1962	1963–1965	1966–1975	1976–1985	1986–2001[c]
Uranium	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
Pu-alpha[a]	1.17E–03	8.21E–04	8.14E–04	8.07E–04	8.02E–04
Pu-241	1.21E–02	8.47E–03	5.23E–03	3.24E–03	2.00E–03
Am-241	7.76E–07	5.45E–07	1.07E–04	1.71E–04	2.09E–04
Np-237	4.04E–04	2.84E–04	2.84E–04	2.84E–04	2.84E–04
Tc-99	1.49E–01	1.05E–01	1.05E–01	1.05E–01	1.05E–01
Th-232	1.61E–06	1.13E–06	1.13E–06	1.13E–06	1.13E–06
Th-228	1.13E–06	7.91E–07	7.91E–07	7.91E–07	7.91E–07
Ru-103/106[b]	1.61E–01	1.13E–01	1.13E–01	1.13E–01	1.13E–01
Zr-95	2.42E–02	1.70E–02	1.70E–02	1.70E–02	1.70E–02
Nb-95	2.42E–02	1.70E–02	1.70E–02	1.70E–02	1.70E–02
Sr-90	6.46E–03	4.53E–03	4.53E–03	4.53E–03	4.53E–03

a. The plutonium alpha mixture is assessed as 100% Pu-239. Am-241 and Pu-241 are assessed based on 6% weapons-grade plutonium mixture.
b. Ru-103/106 is assumed to be 100% Ru-106 due to its longer half-life.
c. The year 2002 is not listed, although a covered period, because all environmental doses in 2002 are zero.

4.2.3.2.2 Radon

WSP

During the postoperational years, outdoor radon was measured at WSP, WSRP, and WSQ (Weidner and Boback 1982, pp. 28–30, 33, 50; Bechtel 1983a, pp. 22–25; 1983b, pp. 22-27; DOE 1984a, pp. 23–26; 1985a, pp. 24–48; 1986, pp. 34–41; 1987, p. 58–63; 1988, pp. 66–73; 1989b, pp. 143–147; 1989a, pp. 80–84; 1990b, pp. 8–17; 1990a, pp. 110–119; 1991, pp. 105, 115–127; 1992a, pp. 75–90; 1992b, pp. 276–277, 431; 1993, pp. 114–124; 1994, pp. 92–103; 1995, pp. 87–10; 1996, pp. 75–91; 1997, pp. 70–88; 1998a, pp. 58–73; 1998b, pp. 32–36; 1999, pp. 67–82; 2000, pp. 63–78; 2001b, pp. 64–76). At WSP, only perimeter measurements occurred except in 1999 and 2000, when some measurements occurred inside the perimeter where the Disposal Cell received much of the remediation wastes. Because there was still some movement of material at the site and workplace monitors were used for the brief period of placement of waste material in the Disposal Cell in 2001 (DOE 2002, pp. 8, 9), the intakes for 2001 were assumed to be equal to the intakes for 2000.

This TBD assumes the average measured radon concentrations at the perimeter stations were underestimates of the average radon concentration over the WSP onsite areas during the remediation period. Therefore, just as for particulates, the measured concentrations were multiplied by 30 to provide an average net radon concentration for the WSP. Table 4-3 lists the derived concentrations, which include contributions of radon from naturally occurring ^{226}Ra and ^{228}Ra. These concentrations reflect total radon (^{222}Rn and ^{220}Rn) as measured by F-type alpha track detectors.

Table 4-3. Daily median intakes for WSP, WSQ, and WSRP.

Year	WSRP U-234[a] (Bq/d)	WSRP radon[b] (WLM/d)	WSP U-234 (Bq/d)	WSP Th-230 (Bq/d)	WSP natural Th (Bq/d)	WSP Rn-220 (WLM/d)	WSP Rn-222[b] (WLM/d)	WSQ U-234 (Bq/d)	WSQ Rn-220 (WLM/d)	WSQ Rn-222[b] (WLM/d)
1957–1959	0.00E+00[c]	0.00E+00[c]	1.86E+00	1.49E+00	0.00E+00	0.00E+00	3.39E–02[d]	0.00E+00	0.00E+00	0.00E+00
1960	0.00E+00[c]	0.00E+00[c]	3.79E+00	3.03E+00	0.00E+00	0.00E+00	3.39E–02[d]	0.00E+00	0.00E+00	0.00E+00
1961	0.00E+00[c]	0.00E+00[c]	6.51E+00	5.20E+00	0.00E+00	0.00E+00	3.39E–02[d]	9.53E–03	0.00E+00	0.00E+00
1962	0.00E+00[c]	0.00E+00[c]	1.60E+00	1.28E+00	0.00E+00	0.00E+00	3.39E–02[d]	6.46E–03	0.00E+00	0.00E+00
1963	0.00E+00[c]	0.00E+00[c]	2.90E+00	2.33E+00	0.00E+00	1.33E–06	3.39E–02[d]	6.97E–03	1.33E–06	3.39E–02[d]
1964	0.00E+00[c]	0.00E+00[c]	2.22E+00	1.77E+00	1.72E–03	7.94E–06	3.39E–02[d]	1.62E–02	7.94E–06	3.39E–02[d]
1965	0.00E+00[c]	0.00E+00[c]	1.21E+00	9.66E–01	3.19E–02	7.94E–06	3.39E–02[d]	1.08E–01	7.94E–06	3.39E–02[d]
1966	0.00E+00[c]	0.00E+00[c]	1.21E+00	9.66E–01	1.04E–01	5.94E–06	3.39E–02[d]	1.08E–01	5.94E–06	3.39E–02[d]
1967–1974	0.00E+00[f]	0.00E+00[f]	0.00E+00[g]	0.00E+00[g]	0.00E+00[g]	0.00E+00	0.00E+00[g]	0.00E+00	0.00E+00[f]	0.00E+00[f]
1975–1976	0.00E+00[c]	1.11E–04	0.00E+00[g]	0.00E+00[g]	0.00E+00[g]	0.00E+00	0.00E+00[g]	1.08E–01	0.00E+00	5.20E–05
1977–1978	0.00E+00[c]	1.59E–04	0.00E+00[g]	0.00E+00[g]	0.00E+00[g]	0.00E+00	0.00E+00[g]	1.08E–01	0.00E+00	5.28E–05
1979	0.00E+00[c]	2.90E–05	0.00E+00[g]	0.00E+00[g]	0.00E+00[g]	0.00E+00	0.00E+00[g]	1.08E–01	0.00E+00	2.90E–05
1980	0.00E+00[c]	1.80E–04	0.00E+00[g]	0.00E+00[g]	0.00E+00[g]	0.00E+00	0.00E+00[g]	1.08E–01	0.00E+00	4.75E–05
1981	0.00E+00[c]	1.18E–04	0.00E+00[g]	0.00E+00[g]	0.00E+00[g]	0.00E+00	0.00E+00[g]	1.08E–01	0.00E+00	6.09E–05
1982	0.00E+00[c]	2.38E–05	0.00E+00[g]	0.00E+00[g]	0.00E+00[g]	0.00E+00	0.00E+00[g]	1.08E–01	0.00E+00	6.92E–05
1983	0.00E+00[c]	1.50E–05	0.00E+00[g]	0.00E+00[g]	0.00E+00[g]	0.00E+00	0.00E+00[g]	1.08E–01	0.00E+00	3.13E–05
1984	0.00E+00[c]	2.57E–05	0.00E+00[g]	0.00E+00[g]	0.00E+00[g]	0.00E+00	0.00E+00[g]	1.08E–01	0.00E+00	3.58E–05
1985	0.00E+00[c]	1.71E–05	4.91E–03	3.92E–03	0.00E+00[h]	0.00E+00	3.21E–04	1.08E–01	0.00E+00	3.58E–05
1986	0.00E+00[c]	2.43E–05	4.91E–03	3.92E–03	0.00E+00[h]	0.00E+00	4.94E–04	1.08E–01	0.00E+00	3.42E–05
1987	0.00E+00	2.00E–05	4.91E–03	3.92E–03	0.00E+00[h]	0.00E+00	6.42E–04	1.08E–01	0.00E+00	6.42E–05
1988	0.00E+00	3.13E–05	4.91E–03	3.92E–03	0.00E+00[h]	0.00E+00	8.78E–04	0.00E+00	0.00E+00	9.72E–05
1989	0.00E+00	2.36E–05	4.91E–03	3.92E–03	0.00E+00[h]	0.00E+00	8.15E–04	0.00E+00	0.00E+00	6.14E–05
1990	1.79E–04	1.43E–05	4.91E–03	3.92E–03	0.00E+00[h]	0.00E+00	5.14E–04	6.11E–05	0.00E+00	4.99E–05
1991	9.00E–05	1.57E–05	2.96E–03	2.37E–03	0.00E+00[h]	0.00E+00	4.28E–04	1.18E–05	0.00E+00	4.28E–05
1992	7.03E–05	1.57E–05	2.21E–03	1.77E–03	0.00E+00[h]	0.00E+00	3.42E–04	0.00E+00	0.00E+00	3.87E–05
1993	8.28E–05	7.13E–06	2.48E–03	1.98E–03	0.00E+00[h]	0.00E+00	1.59E–04	1.12E–05	0.00E+00	8.72E–05
1994	9.72E–05	2.00E–05	3.40E–03	2.71E–03	0.00E+00[h]	0.00E+00	3.63E–04	8.61E–05	0.00E+00	2.43E–04
1995	8.48E–05	2.43E–05	2.75E–03	2.20E–03	0.00E+00[h]	0.00E+00	4.70E–04	2.88E–05	0.00E+00	8.28E–05
1996	1.12E–04	4.07E–05	3.18E–03	2.54E–03	0.00E+00[h]	0.00E+00	5.77E–04	1.18E–05	0.00E+00	1.86E–05
1997	1.35E–04	9.27E–05	2.96E–03	2.37E–03	0.00E+00[h]	0.00E+00	4.70E–04	0.00E+00	0.00E+00	1.57E–05
1998	1.56E–04	1.64E–05	4.15E–03	3.32E–03	0.00E+00[h]	0.00E+00	2.79E–04	9.33E–06	0.00E+00	1.06E–05
1999	1.39E–04	2.64E–05	4.09E–03	3.28E–03	0.00E+00[h]	0.00E+00	5.35E–04	1.33E–06	0.00E+00	2.43E–05
2000	7.36E–05	1.43E–05	2.75E–03	2.20E–03	0.00E+00[h]	0.00E+00	5.56E–04	1.18E–05	0.00E+00	1.86E–05
2001	7.36E–05	1.43E–05	2.75E–03	2.20E–03	0.00E+00[h]	0.00E+00	5.56E–04	1.18E–05	0.00E+00	1.86E–05
2002	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

a. Data are reported as gross alpha rather than uranium. NU is assumed through 1962, and EU is assumed thereafter.
b. Radon refers to both Rn-220 and Rn-222, represented as 100% Rn-222, and includes natural background contribution.
c. No significant airborne concentration was likely because the source term was small and the contents of the pits were covered with water.
d. Assumed radon intake value for the operational period at the WSP.
e. Before 1963, the quarry contained only drummed waste that was typically submerged in water and was therefore a negligible contributor.
f. There were no AEC contractors on site during this period. The National Lead Company of Ohio began environmental monitoring at the WSRP and WSQ in August 1975.
g. DOD control period.
h. No source term for natural thorium.

Table 4-4. Maximum sitewide daily median intakes.

Year	U-234[a] (Bq/d)	Th-228 (Bq/d)	Ra-228 (Bq/d)	Th-230 (Bq/d)	Th-232 (Bq/d)	Pu-239 (Bq/d)	Pu-241 (Bq/d)	Am-241 (Bq/d)	Np-237 (Bq/d)	Tc-99 (Bq/d)	Ru-106 (Bq/d)	Zr-95 (Bq/d)	Nb-95 (Bq/d)	Sr-90 (Bq/d)	Rn-220 (WLM/d)	Rn-222[b] (WLM/d)
1957–1959	1.86E+00	0.00E+00	0.00E+00	1.49E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.39E–02
1960	3.79E+00	0.00E+00	0.00E+00	3.03E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.39E–02
1961	6.51E+00	7.34E–06	0.00E+00	5.20E+00	1.05E–05	7.61E–03	7.85E–02	5.05E–06	2.63E–03	9.72E–01	1.05E+00	1.58E–01	1.58E–01	4.20E–02	0.00E+00	3.39E–02
1962	1.60E+00	1.81E–06	0.00E+00	1.28E+00	2.58E–06	1.88E–03	1.93E–02	1.24E–06	6.48E–04	2.40E–01	2.59E–01	3.88E–02	3.88E–02	1.04E–02	0.00E+00	3.39E–02
1963	2.90E+00	2.30E–06	4.60E–06	2.33E+00	3.28E–06	2.38E–03	2.46E–02	1.58E–06	8.24E–04	3.04E–01	3.29E–01	4.94E–02	4.94E–02	1.32E–02	1.33E–06	3.39E–02
1964	2.22E+00	1.72E–03[f]	3.44E–03[f]	1.77E+00	1.72E–03[e]	1.82E–03	1.88E–02	1.21E–06	6.30E–04	2.33E–01	2.52E–01	3.77E–02	3.77E–02	1.01E–02	7.94E–06	3.39E–02
1965	1.21E+00	3.20E–02[f]	6.41E–02[f]	9.66E-01	3.20E–02[e]	9.93E–04	1.02E–02	6.59E–07	3.43E–04	1.27E–01	1.37E–01	2.05E–02	2.05E–02	5.48E–03	7.94E–06	3.39E–02
1966	1.21E+00	1.05E–01[f]	2.09E–01[f]	9.66E-01	1.05E–01[e]	9.84E–04	6.32E–03	1.29E–04	3.43E–04	1.27E–01	1.37E–01	2.05E–02	2.05E–02	5.48E–03	5.94E–06	3.39E–02
1967–1974	0.00E+00[c]	0.00E+00[c]	0.00E+00[c]	0.00E+00[c]	0.00E+00[c]	0.00E+00[c]	0.00E+00[c]	0.00E+00[c]	0.00E+00[c]	0.00E+00[c]	0.00E+00[c]	0.00E+00[c]	0.00E+00[c]	0.00E+00[c]	0.00E+00[c]	0.00E+00[c]
1975	1.08E–01	8.53E–08	0.00E+00	0.00E+00[d]	1.22E–07	8.77E–05	5.64E–04	1.15E–05	3.06E–05	1.13E–02	1.22E–02	1.83E–03	1.83E–03	4.88E–04	0.00E+00	1.11E–04
1976	1.08E–01	8.54E–08	0.00E+00	0.00E+00[d]	1.22E–07	8.70E–05	3.49E–04	1.84E–05	3.06E–05	1.13E–02	1.22E–02	1.83E–03	1.83E–03	4.89E–04	0.00E+00	1.11E–04
1977	1.08E–01	8.53E–08	0.00E+00	0.00E+00[d]	1.22E–07	8.69E–05	3.49E–04	1.84E–05	3.06E–05	1.13E–02	1.22E–02	1.83E–03	1.83E–03	4.88E–04	0.00E+00	1.59E–04
1978	1.08E–01	8.54E–08	0.00E+00	0.00E+00[d]	1.22E–07	8.70E–05	3.49E–04	1.84E–05	3.06E–05	1.13E–02	1.22E–02	1.83E–03	1.83E–03	4.89E–04	0.00E+00	1.59E–04
1979	1.08E–01	8.53E–08	0.00E+00	0.00E+00[d]	1.22E–07	8.69E–05	3.49E–04	1.84E–05	3.06E–05	1.13E–02	1.22E–02	1.83E–03	1.83E–03	4.88E–04	0.00E+00	2.90E–05
1980	1.08E–01	8.53E–08	0.00E+00	0.00E+00[d]	1.22E–07	8.69E–05	3.49E–04	1.84E–05	3.06E–05	1.13E–02	1.22E–02	1.83E–03	1.83E–03	4.88E–04	0.00E+00	1.80E–04
1981	1.08E–01	8.53E–08	0.00E+00	0.00E+00[d]	1.22E–07	8.69E–05	3.49E–04	1.84E–05	3.06E–05	1.13E–02	1.22E–02	1.83E–03	1.83E–03	4.88E–04	0.00E+00	1.18E–04
1982	1.08E–01	8.53E–08	0.00E+00	0.00E+00[d]	1.22E–07	8.69E–05	3.49E–04	1.84E–05	3.06E–05	1.13E–02	1.22E–02	1.83E–03	1.83E–03	4.88E–04	0.00E+00	6.92E–05
1983	1.08E–01	8.53E–08	0.00E+00	0.00E+00[d]	1.22E–07	8.69E–05	3.49E–04	1.84E–05	3.06E–05	1.13E–02	1.22E–02	1.83E–03	1.83E–03	4.88E–04	0.00E+00	3.13E–05
1984	1.08E–01	8.53E–08	0.00E+00	0.00E+00[d]	1.22E–07	8.69E–05	3.49E–04	1.84E–05	3.06E–05	1.13E–02	1.22E–02	1.83E–03	1.83E–03	4.88E–04	0.00E+00	3.58E–05
1985	1.08E–01	8.53E–08	0.00E+00	3.92E–03	1.22E–07	8.69E–05	3.49E–04	1.84E–05	3.06E–05	1.13E–02	1.22E–02	1.83E–03	1.83E–03	4.88E–04	0.00E+00	3.21E–04
1986	1.08E–01	8.53E–08	0.00E+00	3.92E–03	1.22E–07	8.64E–05	2.16E–04	2.25E–05	3.06E–05	1.13E–02	1.22E–02	1.83E–03	1.83E–03	4.88E–04	0.00E+00	4.94E–04
1987	1.08E–01	8.53E–08	0.00E+00	3.92E–03	1.22E–07	8.64E–05	2.16E–04	2.25E–05	3.06E–05	1.13E–02	1.22E–02	1.83E–03	1.83E–03	4.88E–04	0.00E+00	6.42E–04
1988	4.91E–03	3.88E–09	0.00E+00	3.92E–03	5.55E–09	3.93E–06	9.84E–06	1.02E–06	1.39E–06	5.15E–04	5.56E–04	8.34E–05	8.34E–05	2.22E–05	0.00E+00	8.78E–04
1989	4.91E–03	3.88E–09	0.00E+00	3.92E–03	5.55E–09	3.93E–06	9.84E–06	1.02E–06	1.39E–06	5.15E–04	5.56E–04	8.34E–05	8.34E–05	2.22E–05	0.00E+00	8.15E–04
1990	4.91E–03	3.88E–09	0.00E+00	3.92E–03	5.55E–09	3.93E–06	9.84E–06	1.02E–06	1.39E–06	5.15E–04	5.56E–04	8.34E–05	8.34E–05	2.22E–05	0.00E+00	5.14E–04
1991	2.96E–03	2.35E–09	0.00E+00	2.37E–03	3.35E–09	2.38E–06	5.94E–06	6.18E–07	8.41E–07	3.11E–04	3.36E–04	5.04E–05	5.04E–05	1.34E–05	0.00E+00	4.28E–04
1992	2.21E–03	1.75E–09	0.00E+00	1.77E–03	2.50E–09	1.77E–06	4.42E–06	4.61E–07	6.26E–07	2.31E–04	2.50E–04	3.75E–05	3.75E–05	1.00E–05	0.00E+00	3.42E–04
1993	2.48E–03	1.96E–09	0.00E+00	1.98E–03	2.80E–09	1.99E–06	4.96E–06	5.17E–07	7.03E–07	2.60E–04	2.81E–04	4.21E–05	4.21E–05	1.12E–05	0.00E+00	1.59E–04
1994	3.40E–03	2.69E–09	0.00E+00	2.71E–03	3.84E–09	2.72E–06	6.81E–06	7.09E–07	9.64E–07	3.56E–04	3.85E–04	5.77E–05	5.77E–05	1.54E–05	0.00E+00	3.63E–04
1995	2.75E–03	2.17E–09	0.00E+00	2.20E–03	3.11E–09	2.20E–06	5.50E–06	5.73E–07	7.79E–07	2.88E–04	3.11E–04	4.67E–05	4.67E–05	1.24E–05	0.00E+00	4.70E–04
1996	3.18E–03	2.52E–09	0.00E+00	2.54E–03	3.60E–09	2.55E–06	6.37E–06	6.64E–07	9.02E–07	3.33E–04	3.60E–04	5.40E–05	5.40E–05	1.44E–05	0.00E+00	5.77E–04
1997	2.96E–03	2.35E–09	0.00E+00	2.37E–03	3.35E–09	2.38E–06	5.94E–06	6.18E–07	8.41E–07	3.11E–04	3.36E–04	5.04E–05	5.04E–05	1.34E–05	0.00E+00	4.70E–04
1998	4.15E–03	3.29E–09	0.00E+00	3.32E–03	4.69E–09	3.33E–06	8.32E–06	8.66E–07	1.18E–06	4.35E–04	4.70E–04	7.06E–05	7.06E–05	1.88E–05	0.00E+00	2.79E–04
1999	4.09E–03	3.24E–09	0.00E+00	3.28E–03	4.63E–09	3.28E–06	8.20E–06	8.54E–07	1.16E–06	4.29E–04	4.64E–04	6.96E–05	6.96E–05	1.86E–05	0.00E+00	5.35E–04
2000	2.75E–03	2.17E–09	0.00E+00	2.20E–03	3.11E–09	2.20E–06	5.50E–06	5.73E–07	7.79E–07	2.88E–04	3.11E–04	4.67E–05	4.67E–05	1.24E–05	0.00E+00	5.56E–04
2001	2.75E–03	2.17E–09	0.00E+00	2.20E–03	3.11E–09	2.20E–06	5.50E–06	5.73E–07	7.79E–07	2.88E–04	3.11E–04	4.67E–05	4.67E–05	1.24E–05	0.00E+00	5.56E–04
2002	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.00E+00	0.00E+00	0.00E+00	0.00E+00

a. Data are reported as gross alpha rather than uranium. NU is assumed through 1962, and EU is assumed thereafter.
b. Radon refers to both Rn-220 and Rn-222, represented as 100% Rn-222, and includes natural background contribution.
c. WSP was not a covered facility under EEOICPA and there were no AEC contractors at WSRP or WSQ during this period.
d. DOD control period.
e. Values pertain to processed natural thorium. All other Th-232 values from 1961 to 2001 are RU contaminant values.
f. Values are associated with the processed Th-232 values at ratios of 1:1 for Th-232:Th-228 and 2:1 for Ra-228:Th-232.

WSRP
Radon measurements in WSRP in the late 1970s and early 1980s (before remediation) averaged 34 ±37 Bq/m^3, which indicates that the pits were not a major source of radon (Meshkov et al. 1986, p. 101). This value is limiting for the operational period because the amount of ^{226}Ra in the pits was at its maximum at the end of operations and it would not have decayed or leached out of the pits significantly before the measurements were made.

At WSRP, radon measurements occurred at the perimeter monitoring stations between 1985 and 2000, at one location inside the perimeter during 1985 and 1986, and at several interior locations during the years of active remediation (1998 to 2000). This TBD assumes the average measured radon concentrations at the perimeter stations were underestimates of the average radon concentration over the WSRP onsite areas during the remediation period. Therefore, just as for particulates, the measured concentrations were multiplied by 30 to provide an average net radon concentration for the WSRP. Table 4-3 lists the derived concentrations, which include contributions of radon from naturally occurring ^{226}Ra and ^{228}Ra. These concentrations reflect total radon (^{222}Rn and ^{220}Rn) as measured by F-type alpha track detectors.

WSQ
Measurements in the quarry area in the late 1970s and early 1980s (before remediation) averaged 24 ±15 Bq/m^3, which indicates the quarry was not a major source of radon (Meshkov et al. 1986, p. 101).

At WSQ, radon measurements occurred only at the perimeter monitoring stations except in 1989, when monitors were placed on the quarry floor. The ratio of the average perimeter radon concentration to the average quarry floor concentration was 30. This is a significant increase, but the interior of the quarry is fairly inaccessible, with a quick drop in elevation and an abundance of vegetation. Therefore, this TBD assumes that the perimeter concentrations are reasonably representative of exposure concentrations except during the active removal of the quarry bulk waste in 1993, 1994, and 1995. During this period of active remediation, this TBD assumed the radon concentration to be 30 times the concentration measured at the perimeter (ORAUT 2017c).

4.2.4 Radionuclide Intake Derivation

For the purposes of dose reconstruction, the assumption was made that all uranium processed at WSP was NU from 1957 through 1962, with a specific activity of 683 pCi/mg. After 1962, all uranium was assumed to be enriched to 1%, with a specific activity of 973 pCi/mg (ORAUT 2017b). Most of the RU at WSP came from the Feed Materials Production Center, which in turn received most of its RU from the Hanford Site, which was recycled from uranium that had been irradiated to produce weapons-grade plutonium (ORAUT 2017c). Therefore, a 6% weapons-grade mixture that had been chemically purified in 1961 was selected for dose calculations (ORAUT 2017b; ORAUT 2017c). For dose reconstruction, the plutonium alpha dose from the plutonium mixtures in RU is assumed to be from 100% ^{239}Pu. Plutonium mixture ratios for fresh, 10-, 20-, and 30-year-aged intervals after purification were used to estimate the ^{241}Pu and ^{241}Am contaminant levels (ORAUT 2017b). Table 4-2 lists the RU contaminant intakes per unit activity of uranium.

The TBD analysis used Equation 4-2 to convert the radon concentrations into intake values for periods outside the operational period (i.e., after 1966). The WLM/d intake per Bq/m^3 for ^{222}Rn was calculated as:

$$^{222}Rn\,\frac{WLM/d}{Bq/m^3} = \frac{0.3 \times 2{,}000}{3{,}700 \times 170 \times 365.25} = 2.61 \times 10^{-6} \quad (4\text{-}2)$$

where 0.3 is the equilibrium factor (DOE 2001a, p. 31), 2,000 is the number of hours in a working year, 3,700 is the conversion factor of Bq/m^3 per 100 pCi/L, 170 is the number of hours in a working month, and 365.25 is the average number of days in a calendar year. One Working Level is equal to 100 pCi/L of ^{222}Rn. This is adapted from ORAUT (2017b).

Table 4-1 lists the median airborne radioactivity concentrations used to calculate the radionuclide intake activities. Table 4-2 lists the intake activity ratios of the RU contaminants to uranium. Table 4-3 lists the median intake values for WSP, WSRP, and WSQ, with radon represented as ^{222}Rn. Table 4-4 lists maximum sitewide median intakes across WSP to be represented in the Interactive RadioEpidemiological Program (IREP) as lognormal distributions with a geometric standard deviation (GSD) of 3. The intakes for Tables 4-3 and 4-4 are stated in units of activity per calendar day (ORAUT 2020).

The purpose of Table 4-3 is to assign the WSP worker an estimate of intake for various radionuclides for the three areas (raffinate pits, chemical plant, and quarry). This table can also be used to determine environmental internal doses specific to the worker's work site. The values in Table 4-2 can be used with the uranium values in Table 4-3 to determine the RU contaminant activities associated with the three WSP areas. The purpose of Table 4-4 is to give the DR the maximum median intake for a specific year for use in determining the worker's dose when the specific work location is not known. Table 4-4 would most likely be used by the DR because the calculated dose is favorable to the claimant and expedites completion of the dose reconstruction.

4.3 EXTERNAL EXPOSURE TO ONSITE ATMOSPHERIC RADIONUCLIDE CONCENTRATIONS

External ambient exposure at WSP was a result of gamma and X-ray radiation from radionuclides in the ore concentrate that were stored on the site during the operational period and from radionuclides in WSRP and WSQ. Section 4.3.1 identifies ambient exposures during the operational period, and Section 4.3.2 provides ambient exposures during the postoperational years.

Onsite ambient doses at WSP are to be calculated as best estimates. DRs use a Monte Carlo technique where the uncertainty distributions associated with the onsite ambient dose, either lognormal or normal, is multiplied by the appropriate organ dose conversion factor (DCF), which is a triangular distribution. It is assumed that the worker worked 2,500 hours during the year, 50 hours per week and 50 weeks per year, prorated for partial year employment and scaled as necessary for periods of no exposure potential as determined from the telephone interview or employment records (ORAUT 2018b). The 2,500 work hours per year assumption is also based on a computer-assisted telephone interview query using the first 10 claims which included employment at any of the three facilities (Weldon Spring Plant, Quarry, and Raffinate Pits) and the 20 most recent claims as of July 16, 2019. Nineteen of the selected energy employees indicated overtime work, while the remaining 11 did not.

4.3.1 Operational Period, 1957 to 1966

Available documents do not contain monitoring data that describe the ambient exposure rate at WSP during the operational period. During this period, ambient dose rates in excess of natural background radiation would have been due primarily to gamma radiation from short-lived decay products of ^{238}U in the vicinity of the storage pad for the drums that contained the ore concentrate (Meshkov et al. 1986, p. 46). Exposure to radionuclides that accumulated in WSRP and WSQ would be mitigated somewhat by the shielding and physical barrier that was provided by water that covered the pits entirely and some of the waste in the quarry for much of the year.

Employees who worked in radiological areas were monitored, and their exposures are accounted for in their normal dosimetry results. Because all employees in operational areas were required to wear film dosimeters, there should not have been unmonitored employees subject to exposure in those areas (NIOSH 2010b, pp. 61–64). Because no site-specific ambient exposure data for WSP has been discovered for the operational period, DRs should consider applying the 50th-percentile value (equivalent to median or geometric mean) of the occupational external dose (Table 4-5) for monitored workers during the operational period as the onsite ambient dose for unmonitored workers (ORAUT 2019a). Potential ambient environmental dose for unmonitored workers, such as unbadged administrative personnel, is bounded by the 50th-percentile value of the data for monitored individuals. There are no median values for 1967 because there were no measured external doses associated with the pool of WSP claimants. DRs should adjust the dose by prorating for partial year employment periods and/or partial year external dose monitoring. Although these dose values could be considered favorable to the claimant, in lieu of site-specific ambient exposure information during this period, they are assigned as best estimates.

Table 4-5. Median values for occupational external gamma dose.

Year	Median gamma dose (rem)[a]	GSD
1957	0.161	2.63
1958	0.081	2.15
1959	0.078	2.44
1960	0.126	2.27
1961	0.136	2.94
1962	0.139	2.80
1963	0.220	2.92
1964	0.187	3.14
1965	0.151	3.71
1966	0.123	3.16

a. Calculated as the 50th-percentile value of a lognormal distribution in accordance with Battelle-TIB-5000 (BT 2007; ORAUT 2019a).

4.3.2 Postoperational Years, 1967 to 2002

DOE had no contractors on the site until 1975 when it began air monitoring at WSRP and WSQ. The results of monitoring for ambient exposure from 1975 to 1981 are not available, so the analysis estimated ambient doses for the years from 1975 to 1981 from later data as explained below.

A 1975 aerial radiological survey of WSP (Jobst 1976, p. 32) indicated that the average background gamma exposure rate was 7 to 10 µR/hr. For continuous exposure over a year, this represents an annual ambient dose of 61 to 88 mrem/yr. However, the aerial survey found elevated terrestrial exposures over WSRP and WSQ, which indicated the presence of manmade changes from the natural radioisotopes (NIOSH 2010b, pp. 61–62).

Ambient exposure rates in excess of natural background rates existed before remediation in areas close to waste in WSRP or WSQ (Jobst 1976, p. 32–33). Based on the results of the aerial survey, gamma radiation exposure rate isopleths were drawn in the immediate vicinity of the plant and centered on the raffinate pits. This indicated total exposure rates from 120 to 168 µR/hr with decreasing levels from 15.8 to 35.8 µR/hr at approximately 1,000 ft from the pits (Jobst 1976, p. 32).

4.3.2.1 Weldon Spring Plant

Between 1982 and 2000, ambient exposure was monitored using thermoluminescent dosimeters at many perimeter locations around WSP, WSRP, and WSQ (Bechtel 1983a, pp. 26–27; DOE 1984a, pp. 27–28; 1985a, pp. 28–30; 1986, pp. 40–44; 1987, pp. 64–66, 58–61; 1988, pp. 73–76; 1989b, pp. 147–149; 1989a, pp. 85–90; 1990a, pp. 119–125; 1991, pp. 127–131; 1992a, pp. 90–98; 1992b, pp. 276–277, 432; 1993, pp. 125–128; 1994, pp. 103–106; 1995, pp. 100–104; 1996, pp. 92–95; 1997, pp. 89–92; 1998a, pp. 74–78; 1998b, pp. 32–36; 1999, pp. 82–86; 2000, pp. 78–81; 2001b, pp. 76–79). In 1986, locations in WSP and WSRP were monitored, but the results did not indicate a significant difference in exposure rate from the perimeter stations. Figure 4-3 shows the locations of monitoring stations.

Reported ambient exposure values included background except for 1985 when an average background rate of 99 mrem/yr was subtracted from the total measured values at the monitoring stations. Many of the reported values for 1985 were zero, representing a net value (exposure rate minus background rate) of either zero or less than zero. To use these numbers for 1985, the analysis added the background value of 99 to the reported net value. Therefore, the average ambient exposures for 1985 might be a slight overestimate due to the addition of background to a zero value that actually might have been less than zero.

A 1987 radiologic characterization of WSP and WSRP (Marutzky, Colby, and Cahn 1988, pp. 159–168) used portable scintillation counters to record external radiation in counts per minute at 880 locations across WSRP and WSP. Correlation of those counts with a pressurized ionization chamber allowed estimates of exposure rate in microroentgen per hour. Exposure rates ranged from 9 to 287 µR/hr (at 1 m), which correspond to dose rates between 79 and 2,500 mrem/yr for continuous exposure for 8,760 hr/yr. Fewer than 10% of the 880 surveyed locations had exposure rates of 15 µR/hr or greater. The 95th percentile of the exposure rates is approximately 18 µR/hr. This is reasonable because few of the exposure rates over 15 µR/hr exceed 20 µR/hr, and many of the contaminated areas were probably not those in which occupational exposures would normally have occurred. The elevated exposure rates were in the areas around the buildings, onsite dump areas, the Ash Pond, and drainages of Frog Pond, but it is not possible to sort out exposure rates as a function of location in the reports. An exposure rate of 18 µR/hr represents an annual dose of 158 mrem/yr for continuous exposure. In 1987, the reported WSP perimeter exposure rate was 72 mrem/yr. Therefore, the TBD analysis assumed that, until remediation of WSP was essentially complete in 2000, the average onsite exposure rate was approximately twice the measured perimeter rate.

4.3.2.2 Weldon Spring Raffinate Pits

Measured exposure rates are not available for 1975 through 1982 for WSRP. It is reasonable to assume that the average of the exposure rates from 1983 through 1989 for WSRP adequately represent these earlier years, when the entire site was essentially undisturbed.

A comprehensive radiological survey of the WSRP in 1982 and 1983 indicated an average onsite gamma exposure rate of 23 µR/hr for that site (DOE 1984b, p. 22), which gives a dose rate of approximately 200 mrem/yr for continuous exposure (8,760 hr/yr). This is higher than the perimeter monitors reported for the WSRP before remediation. For 1975 through 1983, 201 mrem/yr is the average survey value for 1982 to 1983 from DOE (1984b, p. 22) because it is considered the best value to use for those years. A comparison of the average survey-based value (201 mrem/yr, adjusted to 57 mrem/yr for a 2,500-hour work year) to the average perimeter value in 1983 (88 mrem/yr) (DOE 1984a, p. 27) suggests the area inside the WSRP perimeter is more appropriately characterized by an exposure rate approximately twice the average perimeter values. The modified ambient dose rates in Table 4-6 represent twice the average perimeter values for 1984 through 2000

and are recommended for environmental dose reconstruction. Figure 4-3 shows the locations of monitoring stations. From 2001 to 2002, after the completion of remediation of most of WSP (DOE 2001b, p.79), the measured dose rate result has not been factored.

4.3.2.3 Weldon Spring Quarry

Measured exposure rates are not available for 1975 through 1981 for WSQ. It is reasonable to assume that the average of the exposure rates from 1982 through 1989 for WSQ adequately represent these earlier years, when the entire site was essentially undisturbed.

A similar radiological survey of WSQ in 1984 and 1985, before remediation, indicated gamma exposure rates from 8 µR/hr (similar to the overall area background rate) to 286 µR/hr over the quarry floor where contamination was greatest (DOE 1985b, p. 29). This single maximum result is provided to indicate the upper measured exposure rate in the quarry. The survey report stated that characterization of WSQ was "extremely difficult because of the rough terrain," and that "the area was densely vegetated" (DOE 1985b). Figure 4-5 includes a topographic map of the WSQ area, along with locations of gamma exposure rate measurements. The survey included many of the relatively inaccessible areas of the quarry, where significant exposure was unlikely except during excavation of quarry bulk wastes. Therefore, the perimeter exposure rates in Table 4-6 are appropriate for estimating exposures except during the excavation period, which occurred during most of 1993, 1994, and 1995 (DOE 1994, pp. 44–45; 1995, p. 48; 1996, pp. 50–51). Figure 4-5 shows the locations of monitoring stations. In Table 4-5, the average value as presented in annual environmental reports is considered the best value for dose reconstruction.

Table 4-6 lists the average onsite ambient dose rates when specific work locations are known. Table 4-7 lists the sitewide maximum external exposure rates among the three sites and should be used when the work locations are either unknown or when the energy employee worked at multiple facilities.

4.3.3 Organ Dose Conversion Factors

The calculated annual dose should be multiplied by the appropriate DCFs in OCAS-IG-001, *External Dose Reconstruction Implementation Guideline* (NIOSH 2007) or ORAUT-OTIB-0088, *External Dose Reconstruction* (ORAUT 2018b), for an isotropic exposure geometry. For the operational period from (1957 to1966) and initial cleanup period (1967 to 1969), the exposure (*R*)-to-organ DCF is used. For the period from 1975 to 1983, the ambient dose equivalent-to-organ DCF is used because those data are based on survey measurements or calculations (ORAUT 2018b). For the period after 1983, the exposure (*R*)-to-organ DCF is used.

4.4 UNCERTAINTY

For external doses and the operational period from 1957 through 1966, the median of a lognormal distribution and its associated GSD are assigned from Table 4-5 as Parameter 1 and 2 in the Interactive RadioEpidemiological Program, respectively. For the postoperational external doses, the onsite ambient dose is represented as a normal distribution with a standard deviation of 30% (Section 6.7.1 of ORAUT 2012).

For internal doses, the environmental internal doses are assigned as lognormal distributions with a GSD of 3.

Table 4-6. Estimated onsite ambient doses.[a]

Year	WSRP average (mrem/yr)[b]	WSP average (mrem/yr)[c]	WSQ average (mrem/yr)[d]
1957–1966	(e)	(e)	Not significant
1975–1981	57	(f)	28
1982	57	(f)	24
1983	57	(f)	27
1984	70	(f)	36
1985	65	57	35
1986	52	45	28
1987	40	41	27
1988	34	36	21
1989	37	40	23
1990	36	38	22
1991	40	43	24
1992	39	39	21
1993	33	36	19
1994	34	35	19
1995	41	40	19
1996	47	39	18
1997	53	39	17
1998	40	36	16
1999	35	35	16
2000	18	32	14
2001	18[g]	32[g]	14[g]
2002	0	0	0

a. Based on 8,760 hr/yr exposure; adjusted for 2,500-hour work year; includes contributions from natural background.
b. From 1984 to 2000, average value is twice the average of the measured values at perimeter locations for the WSRP.
c. Before 2001, average value is twice the average of the measured values at perimeter locations for the WSP.
d. Values are the average of the measured values at perimeter locations for the WSQ.
e. Apply the 50th-percentile occupational external dose from Table 4-5 or evaluate on a case-by-case basis.
f. WSP did not transfer to DOE until 1985.
g. Not monitored after 2000; assumed equal to average for 2000 for respective location.

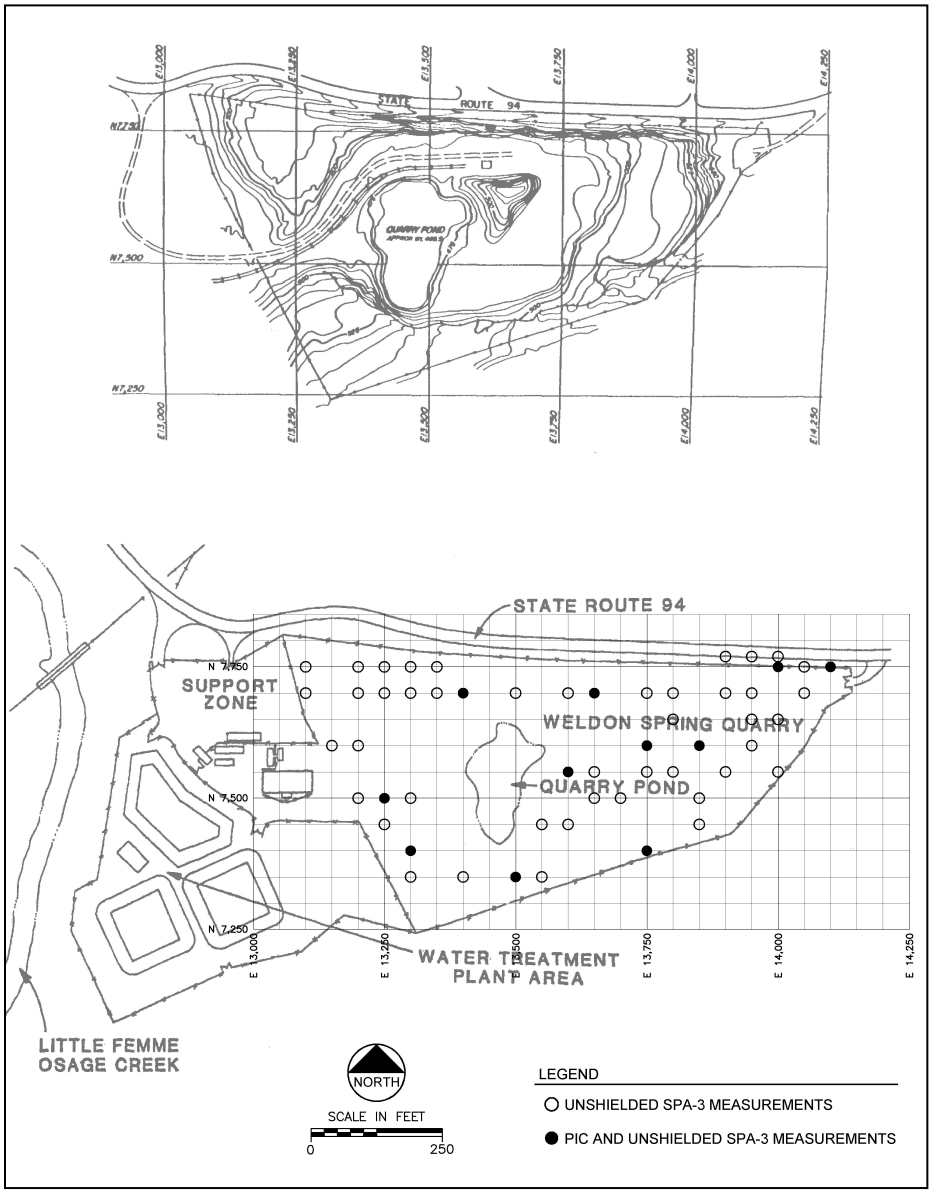

Figure 4-5. Topographic map and locations of gamma exposure rate measurements for WSQ (DOE 1985b, pp. 14, 17).

4.5 SUMMARY ENVIRONMENTAL DOSE DEFAULT VALUES

This section summarizes the tables that list the recommended default values for inhalation intakes and ambient dose. Section 4.2.2.1 refers to ORAUT-TKBS-0017-5 (ORAUT 2017c) in relation to the RU contaminants and their mass concentrations to be applied beginning in 1961.

- Table 4-1 lists the median airborne concentrations for WSP, WSRP, and WSQ.
- Table 4-2 lists the RU contaminant-to-uranium intake ratios.
- Table 4-3 lists the daily median intake values for WSP, WSRP, and WSQ.

Table 4-7. Estimated maximum sitewide ambient dose at WSP.[a,b]

Year	Maximum for WSRP, WSP, and WSQ (mrem/yr)
1957–1966	(c)
1975–1983	57
1984	70
1985	65
1986	52
1987	41
1988	36
1989	40
1990	38
1991	43
1992	39
1993	36
1994	35
1995	41
1996	47
1997	53
1998	40
1999	35
2000	32
2001	32[d]
2002	0

a. Maximum of annual recommended average value for each area (from Table 4-5).
b. Based on 8,760-hr/yr exposure, adjusted for a 2,500-hour work year.
c. Apply the 50th-percentile occupational external dose from Table 4-5 or evaluate on a case-by-case basis.
d. Not monitored after 2000; assumed to be equal to the sitewide maximum for WSP for 2000.

- Table 4-4 lists maximum sitewide estimated daily median inhalation intakes of radioactive air particulates and radon.

- Table 4-5 lists the 50th-percentile values for external environmental dose for unmonitored workers during the operational period. Although potentially favorable to claimants, they are considered best estimates.

- Table 4-6 lists estimated average ambient onsite doses for WSRP, WSP, and WSQ.

- Table 4-7 provides the maximum sitewide estimates of ambient dose, which should be used for a best estimate when the work locations are either unknown or include multiple locations.

DRs should consider the naturally occurring isotopes of uranium (^{234}U, ^{235}U, and ^{238}U) and their progeny (primarily ^{230}Th and ^{226}Ra) when calculating and assigning doses to unmonitored workers from the occupational environmental isotopic air species.

4.6 ATTRIBUTIONS AND ANNOTATIONS

All information requiring identification was addressed via references integrated into the reference section of this document.

REFERENCES

Army (U.S. Department of the Army), 1976, *Assessment of Weldon Spring Chemical Plant in St. Charles, County, Missouri*, Office of the Deputy Assistant Project Manager for Chemical Demilitarization and Installation Restoration, Aberdeen Proving Ground, Maryland, March 1. [SRDB Ref ID: 32709]

Author unknown, 1967, *Weldon Spring Raffinate Pits and Quarry Task Force Report*, June 1. [SRDB Ref ID: 14763]

Bechtel (Bechtel National), 1983a, *Weldon Spring Site (WSS) Environmental Monitoring Report, Calendar Year 1982*, Oak Ridge, Tennessee, May. [SRDB Ref ID: 13376]

Bechtel (Bechtel National), 1983b, *Weldon Spring Site (WSS) Environmental Monitoring Report, Calendar Year 1981*, Oak Ridge, Tennessee, May. [SRDB Ref ID: 13338]

BT (Battelle Team), 2007, *Default Assumptions and Methods for Atomic Weapons Employer Dose Reconstructions*, Battelle-TIB-5000, Rev. 00, Richland, Washington, April 2. [SRDB Ref ID: 32016]

DOE (U.S. Department of Energy), 1984a, *Weldon Spring Site Environmental Monitoring Report, Calendar Year 1983*, DOE/OR/20722-16, Oak Ridge, Tennessee, June. [SRDB Ref ID: 12530]

DOE (U.S. Department of Energy), 1984b, *Radiological Survey Report for the Weldon Spring Raffinate Pits Site*, DOE/OR/20722-7, Oak Ridge, Tennessee, August. [SRDB Ref ID: 12540]

DOE (U.S. Department of Energy), 1985a, *Weldon Spring Site Environmental Monitoring Report, Calendar Year 1984*, DOE/OR/20722-58, Oak Ridge, Tennessee, July. [SRDB Ref ID: 12532]

DOE (U.S. Department of Energy), 1985b, *Radiological Survey Report for the Weldon Spring Quarry*, DOE/OR/20722-70, Oak Ridge, Tennessee, September. [SRDB Ref ID: 3566]

DOE (U.S. Department of Energy), 1986, *Weldon Spring Site Annual Site Environmental Monitoring Report, Calendar Year 1985*, DOE/OR/20722-101, Oak Ridge, Tennessee, September. [SRDB Ref ID: 12533]

DOE (U.S. Department of Energy), 1987, *Weldon Spring Site Annual Environmental Monitoring Report, Calendar Year 1986*, DOE/OR/21548-T1, Oak Ridge Operations Office, Oak Ridge, Tennessee. [SRDB Ref ID: 12535]

DOE (U.S. Department of Energy), 1988, *Weldon Spring Site Annual Environmental Monitoring Report, Calendar Year 1987*, DOE/OR/21548-015, Oak Ridge Operations Office, Oak Ridge, Tennessee. [SRDB Ref ID: 12536]

DOE (U.S. Department of Energy), 1989a, *Annual Environmental Monitoring Report, 1988, for the Weldon Spring Site Remedial Action Project*, DOE/OR/21548-079, Rev. 0, Oak Ridge Operations Office, Oak Ridge, Tennessee, June. [SRDB Ref ID: 13170]

DOE (U.S. Department of Energy), 1989b, *Remedial Investigations for Quarry Bulk Wastes*, DOE/OR/21548-066, Rev. 1, Oak Ridge Operations Office, Oak Ridge, Tennessee, December. [SRDB Ref ID: 12348]

DOE (U.S. Department of Energy), 1990a, *Annual Site Environmental Report, 1989, for the Weldon Spring Site Remedial Action Project*, DOE/OR/21548-129, Rev. 1, Oak Ridge Operations Office, Oak Ridge, Tennessee, November. [SRDB Ref ID: 14901]

DOE (U.S. Department of Energy), 1990b, *Evaluation of Radon Emissions and Potential Control Requirements*, Rev. 2, DOE/OR/21548-082-Rev. 2, Oak Ridge Operations Office, Oak Ridge, Tennessee, January. [SRDB Ref ID: 13513]

DOE (U.S. Department of Energy), 1991, *Annual Site Environmental Report for Calendar Year 1990, Weldon Spring Site Remedial Action Project, Weldon Spring, Missouri,* DOE/OR/21548-193, Rev. 1, Oak Ridge Operations Office, Oak Ridge, Tennessee, September. [SRDB Ref ID: 14902]

DOE (U.S. Department of Energy), 1992a, *Weldon Spring Site Environmental Report for Calendar Year 1991*, DOE/OR/21548-283, Oak Ridge Operations Office, Oak Ridge, Tennessee, August 20. [SRDB Ref ID: 12350]

DOE (U.S. Department of Energy), 1992b, *Remedial Investigation for the Chemical Plant Area of the Weldon Spring Site, Volume I*, DOE/OR/21548-074, Oak Ridge Field Office, Oak Ridge, Tennessee, November. [SRDB Ref ID: 13545]

DOE (U.S. Department of Energy), 1993, *Weldon Spring Site Environmental Report for Calendar Year 1992*, DOE/OR/21548-372, Rev. 0, Oak Ridge Field Office, St. Charles, Missouri, June. [SRDB Ref ID: 13175]

DOE (U.S. Department of Energy), 1994, *Weldon Spring Site Environmental Report for Calendar Year 1993*, DOE/OR/21548-436, Rev. 0, Oak Ridge Operations Office, Oak Ridge, Tennessee, May. [SRDB Ref ID: 14990]

DOE (U.S. Department of Energy), 1995, *Weldon Spring Site Environmental Report for Calendar Year 1994*, DOE/OR/21548-512, Rev. 0, Oak Ridge Operations Office, Oak Ridge, Tennessee, May. [SRDB Ref ID: 14991]

DOE (U.S. Department of Energy), 1996, *Weldon Spring Site Environmental Report for Calendar Year 1995*, DOE/OR/21548-592, Rev. 0, Oak Ridge Operations Office, Oak Ridge, Tennessee, June. [SRDB Ref ID: 14992]

DOE (U.S. Department of Energy), 1997, *Weldon Spring Site Environmental Report for Calendar Year 1996*, DOE/OR/21548-676, Rev. 0, Oak Ridge Operations Office, Oak Ridge, Tennessee, July. [SRDB Ref ID: 12356]

DOE (U.S. Department of Energy), 1998a, *Weldon Spring Site Environmental Report for Calendar Year 1997*, DOE/OR/21548-730, Rev. 0, Oak Ridge Operations Office, Oak Ridge, Tennessee, August. [SRDB Ref ID: 12352]

DOE (U.S. Department of Energy), 1998b, *Remedial Investigation for the Quarry Residuals Operable Unit of the Weldon Spring Site, Weldon Spring, Missouri, Volume I*, DOE/OR/21548-587, Rev. 2 (Final), Oak Ridge Operations Office, Oak Ridge, Tennessee, February. [SRDB Ref ID: 13554]

DOE (U.S. Department of Energy), 1999, *Weldon Spring Site Environmental Report for Calendar Year 1998*, DOE/OR/21548-773, Rev. 0, Oak Ridge Operations Office, Oak Ridge, Tennessee, July. [SRDB Ref ID: 14941]

DOE (U.S. Department of Energy), 2000, *Weldon Spring Site Environmental Report for Calendar Year 1999*, DOE/OR/21548-845, Rev. 0, Oak Ridge Operations Office, Oak Ridge, Tennessee, July. [SRDB Ref ID: 14993]

DOE (U.S. Department of Energy), 2001a, *Internal Dosimetry Program Technical Basis Manual*, DOE/OR/21548-241, Rev. 7, Oak Ridge Operations Office, Oak Ridge, Tennessee, December. [SRDB Ref ID: 32724]

DOE (U.S. Department of Energy), 2001b, *Weldon Spring Site Environmental Report for Calendar Year 2000*, DOE/OR/21548-886, Rev. 0, Oak Ridge Operations Office, Oak Ridge, Tennessee, July. [SRDB Ref ID: 12353]

DOE (U.S. Department of Energy), 2002, *Weldon Spring Site Environmental Report for Calendar Year 2001*, DOE/OR/21548-917, Rev. 0, Oak Ridge Operations Office, Oak Ridge, Tennessee, July. [SRDB Ref ID: 14994]

DOE (U.S. Department of Energy), 2003, *Weldon Spring Site Environmental Report for Calendar Year 2002*, DOE/GJ/79491-931, Rev. 0, Oak Ridge Operations Office, Oak Ridge, Tennessee, May. [SRDB Ref ID: 12355]

DOE (U.S. Department of Energy), 2006, *Weldon Spring Site Third Five-Year Review*, DOE-LM/GJ1158-2006, Office of Legacy Management, Grand Junction, Colorado, September. [SRDB Ref ID: 86462]

DOE (U.S. Department of Energy), 2009, *Guide of Good Practices for Occupational Radiation Protection in Uranium Facilities*, DOE-STD-1136-2009, Washington, D.C., July. [SRDB Ref ID: 97381]

Harris, R. A., 1986, *Historical Nuclear Materials Balance Report for the Former AEC-Owned Weldon Spring Chemical Plant, Weldon Spring, Missouri*, DOE/OR-872, U. S. Department of Energy, Oak Ridge Operations Office, Oak Ridge, Tennessee, July. [SRDB Ref ID: 8252]

ICRP (International Commission on Radiological Protection), 1994, *Human Respiratory Tract Model for Radiological Protection*, Publication 66, Pergamon Press, Oxford, England. [SRDB Ref ID: 22732]

ISCO (Illinois State Climatologist Office), 2009, "Wind Roses and Wind Frequency Tables for Illinois, Station #13994 - St Louis/Lambert Int'l Arpt, MO," Champaign, Illinois. [SRDB Ref ID: 120736]

Jobst, J. E., 1976, *Aerial Radiological Survey of the Weldon Spring Chemical Plant (St. Charles, Missouri), Date of Survey: 22 November 1975*, EGG-1183-1688, EG&G, Las Vegas Operations, Las Vegas, Nevada, April 21. [SRDB Ref ID: 14355]

Marutzky, S. J., R. Colby, and L. S. Cahn, 1988, *Radiologic Characterization of the Weldon Spring, Missouri, Remedial Action Site*, DOE/ID/12584-22, UNC Geotech, Grand Junction, Colorado, February. [SRDB Ref ID: 12539]

Mason, M. G, 1958, "Weldon Spring Raffinate Radioactivity Survey," memorandum to S. H. Anonsen, Mallinckrodt Chemical Works, Weldon Spring, Missouri, December 9. [SRDB Ref ID: 15016]

MCW (Mallinckrodt Chemical Works), 1961a, *Annual Off-Site Environmental Monitoring Report – 1960*, Weldon Spring Plant, Weldon Spring, Missouri. [SRDB Ref ID: 13762]

MCW (Mallinckrodt Chemical Works), 1961b, "Section II, Environmental Monitoring Report, Part I - 4th Quarter 1960," and "Environmental Monitoring Report, Part II - Year 1960," Weldon Spring Plant, Weldon Spring, Missouri. [SRDB Ref ID: 13782]

MCW (Mallinckrodt Chemical Works), 1961c, *Off-Site Environmental Monitoring Report, 3rd Quarter 1961*, Weldon Spring Plant, Weldon Spring, Missouri. [SRDB Ref ID: 15287]

MCW (Mallinckrodt Chemical Works), 1962a, *Personnel and Environmental Monitoring Report, First Quarter 1962*, Weldon Spring Plant, Weldon Spring, Missouri. [SRDB Ref ID: 13732, p. 3]

MCW (Mallinckrodt Chemical Works), 1962b, *Personnel and Environmental Monitoring Report, Second Quarter 1962*, Weldon Spring Plant, Weldon Spring, Missouri. [SRDB Ref ID: 13732, p. 33]

MCW (Mallinckrodt Chemical Works), 1962c, *Personnel and Environmental Monitoring Report, Third Quarter 1962*, Weldon Spring Plant, Weldon Spring, Missouri. [SRDB Ref ID: 13732, p. 73]

MCW (Mallinckrodt Chemical Works), 1964a, *Second Semiannual and Annual Summary Off-Site Environmental Monitoring Report - 1963*, Weldon Spring Plant, Weldon Spring, Missouri, January 28. [SRDB Ref ID: 11803]

MCW (Mallinckrodt Chemical Works), 1964b, *First Semiannual Off-Site Environmental Monitoring Report - 1964*, Weldon Spring Plant, Weldon Spring, Missouri, July 22. [SRDB Ref ID: 11802]

MCW (Mallinckrodt Chemical Works), 1965, *Second Semiannual and Annual Summary Off-Site Environmental Monitoring Report - 1964*, Weldon Spring Plant, Weldon Spring, Missouri, February 8. [SRDB Ref ID: 11816, p. 5]

MCW (Mallinckrodt Chemical Works), 1966, *Semiannual and Annual Summary Off-Site Environmental Monitoring Report - 1965*, Weldon Spring Plant, Weldon Spring, Missouri. [SRDB Ref ID: 14750]

Meshkov, N., P. Benioff, J. Wang, and Y. Yuan, 1986, *Weldon Spring Historical Dose Estimate*, ANL/EES-TM-308, Argonne National Laboratory, Argonne, Illinois, July. [SRDB Ref ID: 13117]

Napier B. A., and J. V. Ramsdell, Jr., 2005, *Atmospheric Data Package for the Composite Analysis*, PNNL-14599, Rev. 1, Battelle Memorial Institute, Pacific Northwest National Laboratory, Richland, Washington, September. [SRDB Ref ID: 86460]

NIOSH (National Institute for Occupational Safety and Health), 2007, *External Dose Reconstruction Implementation Guideline*, OCAS-IG-001, Rev. 3, Office of Compensation Analysis and Support, Cincinnati, Ohio, November 21. [SRDB Ref ID: 38864]

NIOSH (National Institute for Occupational Safety and Health), 2010a, *Radiation Exposures Covered for Dose Reconstructions under Part B of the Energy Employees Occupational Illness Compensation Program Act*, DCAS-IG-003, Rev. 1, Division of Compensation Analysis and Support, Cincinnati, Ohio, October 5. [SRDB Ref ID: 88929]

NIOSH (National Institute for Occupational Safety and Health), 2010b, *SEC Petition Evaluation Report, Petition SEC-00143*, Rev. 0, Office of Compensation Analysis and Support, Cincinnati, Ohio, April 16. [SRDB Ref ID: 122688]

NIOSH (National Institute for Occupational Safety and Health), 2012a, "Advisory Board on Radiation and Worker Health, Work Group on Weldon Spring, Monday, September 10, 2012," transcript, Washington, D.C., September 10. [SRDB Ref ID: 120452]

NIOSH (National Institute for Occupational Safety and Health), 2012b, "Advisory Board on Radiation and Worker Health, 86th Meeting, Wednesday, September 19, 2012," transcript, Washington, D.C., September 19. [SRDB Ref ID: 123610]

NLO (National Lead Company of Ohio), 1977, *Study of Radioactive Waste Storage Areas at ERDA-Weldon Spring Site*, NLCO-1144, Cincinnati, Ohio, April 25. [SRDB Ref ID: 3576]

ORAUT (Oak Ridge Associated Universities Team), 2012, *Site Profile and Technical Basis Document Development,* ORAUT-PROC-0031, Rev 04, November 5. [SRDB Ref ID: 166849]

ORAUT (Oak Ridge Associated Universities Team), 2017a, *Weldon Spring Plant – Site Description*, ORAUT-TKBS-0028-2, Rev. 03, Oak Ridge, Tennessee, September 12. [SRDB Ref ID: 167775]

ORAUT (Oak Ridge Associated Universities Team), 2017b, *Weldon Spring Plant – Occupational Internal Dose*, ORAUT-TKBS-0028-5, Rev. 04, Oak Ridge, Tennessee, August 31. [SRDB Ref ID: 167581]

ORAUT (Oak Ridge Associated Universities Team), 2017c, *Feed Materials Production Center – Occupational Internal Dose*, ORAUT-TKBS-0017-5, Rev. 03, Oak Ridge, Tennessee, March 30. [SRDB Ref ID: 166129]

ORAUT (Oak Ridge Associated Universities Team), 2018a, *Internal Dose Reconstruction*, ORAUT-OTIB-0060, Rev. 02, Oak Ridge, Tennessee, April 20. [SRDB Ref ID: 171554]

ORAUT (Oak Ridge Associated Universities Team), 2018b, *External Dose Reconstruction,* ORAUT-OTIB-0088, Rev 00, September 25. [SRDB Ref ID: 174087]

ORAUT (Oak Ridge Associated Universities Team), 2019a, "Median Beta Gamma Exposures-Operational Period WSP.exe," spreadsheet, Oak Ridge, Tennessee, February 15. [SRDB Ref ID: 175449]

ORAUT (Oak Ridge Associated Universities Team), 2019b, "WSP TBD-4 Rev 04 November 2019 RLM-DPH.xlsx," spreadsheet, Oak Ridge, Tennessee, November 19. [SRDB Ref ID: 178631]

ORAUT (Oak Ridge Associated Universities Team), 2020, "WSP TBD-4 Rev 04 Convert Airborne CCN to Intake Activities.xlsx," spreadsheet, Oak Ridge, Tennessee, January 28. [SRDB Ref ID: 179409]

Sears, M. B., 1976, *Airborne Effluent Control at Uranium Mills*, ORNL Conf-760806-4, Union Carbide Corporation, Oak Ridge National Laboratory, Oak Ridge, Tennessee, August 6. [SRDB Ref ID: 76578]

Sears, M. B., R. E. Blanco, R. C. Dahlman, G. S. Hill, A. D. Ryon, and J. P. Witherspoon, 1975, *Correlation of Radioactive Waste Treatment Costs and the Environmental Impact of Waste Effluents in the Nuclear Fuel Cycle for Use in Establishing "As Low As Practicable" Guides – Milling of Uranium Ores*, ORNL-TM-4903, Vol. 1, Union Carbide Corporation, Oak Ridge National Laboratory, Oak Ridge, Tennessee, May. [SRDB Ref ID: 76582]

Usman, S. S., H. Spitz, and J. Weisman, 2005, *Transport of Radon in Still Water under Steady-State and Transient Conditions*, University of Cincinnati, Cincinnati, Ohio. [SRDB Ref ID: 85465]

Weidner, R. B., and M. W. Boback, 1982, *Weldon Spring Storage Site Environmental Monitoring Report for 1979 and 1980*, NLCO-1176, National Lead Company of Ohio, Cincinnati, Ohio, April 19. [SRDB Ref ID: 14356]

GLOSSARY

alpha particle
See *alpha radiation*.

alpha radiation
Positively charged particle emitted from the nuclei of some radioactive elements. An alpha particle consists of two neutrons and two protons (a helium nucleus) and has an electrostatic charge of +2.

becquerel (Bq)
International System unit of radioactivity equal to 1 disintegration per second; 1 curie equals 37 billion (3.7×10^{10}) Bq.

curie (Ci)
Traditional unit of radioactivity equal to 37 billion (3.7×10^{10}) becquerels, which is approximately equal to the activity of 1 gram of pure ^{226}Ra.

exposure
(1) In general, the act of being exposed to ionizing radiation. (2) Measure of the ionization produced by X- and gamma-ray photons in air in units of roentgens.

gamma radiation
Electromagnetic radiation (photons) of short wavelength and high energy (10 kiloelectron-volts to 9 megaelectron-volts) that originates in atomic nuclei and accompanies many nuclear reactions (e.g., fission, radioactive decay, and neutron capture). Gamma photons are identical to X-ray photons of high energy; the difference is that X-rays do not originate in the nucleus.

isotope
One of two or more atoms of a particular element that have the same number of protons (atomic number) but different numbers of neutrons in their nuclei (e.g., ^{234}U, ^{235}U, and ^{238}U). Isotopes have very nearly the same chemical properties.

nuclide
Stable or unstable isotope of any element. Nuclide relates to the atomic mass, which is the sum of the number of protons and neutrons in the nucleus of an atom. A radionuclide is an unstable nuclide.

radiation
Subatomic particles and electromagnetic rays (photons) with kinetic energy that interact with matter through various mechanisms that involve energy transfer.

radioactivity
Property possessed by some elements (e.g., uranium) or isotopes (e.g., ^{14}C) of spontaneously emitting energetic particles (electrons or alpha particles) by the disintegration of their atomic nuclei. See *radionuclide*.

radionuclide
Radioactive nuclide. See *nuclide*.

raffinate
A product that has had a component or components chemically removed. In this case, waste from uranium or thorium extraction as well as solids from the neutralization of this waste.

rem

Traditional unit of radiation dose equivalent that indicates the biological damage caused by radiation equivalent to that caused by 1 rad of high-penetration X-rays multiplied by a quality factor. The sievert is the International System unit; 1 rem equals 0.01 sievert. The word derives from roentgen equivalent in man; rem is also the plural.

special uranium microcurie

The sum of 3.7×10^4 disintegrations per second from ^{238}U, 3.7×10^4 disintegrations per second from ^{234}U, and 9×10^2 disintegrations per second from ^{235}U.

thermoluminescent dosimeter

Device for measuring radiation dose that consists of a holder containing solid chips of material that, when heated, release the stored energy as light. The measurement of this light provides a measurement of absorbed dose. Thermoluminescent dosimeters replaced film dosimeters at essentially all U.S. Department of Energy sites beginning in the 1960s.

X-ray radiation

Electromagnetic radiation (photons) produced by bombardment of atoms by accelerated particles. X-rays are produced by various mechanisms including bremsstrahlung and electron shell transitions within atoms (characteristic X-rays). Once formed, there is no difference between X-rays and gamma rays, but gamma photons originate inside the nucleus of an atom.