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Weldon Spring Plant – Occupational Environmental Dose

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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.

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ACRONYMS AND ABBREVIATIONS

AEC	U.S. Atomic Energy Commission
AWE	atomic weapons employer
Bq	becquerel
Ci	curie
cm	centimeter
DCAS	Division of Compensation Analysis and Support
DCF	dose conversion factors
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
ft	feet
hr	hour
IREP	Interactive RadioEpidemiological Program
m	meter
mrem	millirem
MT	metric ton
NIOSH	National Institute for Occupational Safety and Health
NLO	National Lead Company of Ohio
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
WSP	Weldon Spring Plant
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 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 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). These documents may be used to assist NIOSH staff in the evaluation of Special Exposure Cohort (SEC) petitions and the completion of the individual work required for each dose reconstruction.

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 terms AWE and DOE facility are defined in sections 7384l(5) and (12) of the Energy Employees Occupational Illness Compensation Program Act of 2000 (EEOICPA), respectively. An AWE facility means "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 U.S.C. § 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 … 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 with regard to which DOE has or had a proprietary interest, or "entered into a contract with an entity to provide management and operation, management and integration, environmental remediation services, construction, or maintenance services." 42 U.S.C. § 7384l(12). The Department of Energy (DOE) determines whether a site meets the statutory definition of an AWE facility and the Department of Labor (DOL) determines if a site is a DOE facility and, if it is, designates it as such.

Accordingly, a Part B 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., covered employee). After DOL determines that a claim meets the eligibility requirements under 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. Unlike the abovementioned statutory provisions on DOE facility definitions that contain specific descriptions or exclusions on facility designation, the statutory provision governing types of exposure to be included in dose reconstructions for DOE covered employees only requires that such exposures be incurred in the performance of duty. As such, NIOSH broadly construes radiation exposures incurred in the performance of duty to include all radiation exposures received as a condition of employment at covered DOE facilities in its dose reconstructions for covered employees. For covered employees at DOE facilities, individual dose reconstructions may also include radiation exposures related to the Naval Nuclear Propulsion Program at DOE facilities, if applicable. No efforts are made to determine the eligibility of any fraction of total measured exposure 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 2010a):

- Background radiation, including radiation from naturally occurring radon present in conventional structures
- 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 as a result of submersion and ambient exposure at WSP.

4.1.2 Scope

Historically, the Weldon Spring Plant has been called the Weldon Spring Site, Weldon Spring Chemical Plant, 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, or 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 during only 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 the WSP. WSQ and WSRP employment is covered during those periods and from 1975 to 1985 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 WSQ was transferred from the U.S. Army to AEC in 1958. There is some potential applicability of shutdown operations in 1967 before transfer of the WSP back to the Army in December 1967. The WSRP and the WSQ remained DOE property. From 1968 to early 1969, the Army began decontamination and dismantling operations to support herbicide production. However, the project was canceled in February 1969, after which the Army placed the WSP in care and custody status. DOE and its predecessors did not have contractors at the WSRP or the WSQ until August 1975 for environmental monitoring. From 1969 to 1981, the status of the three areas did not change. The WSP was transferred from the Army to DOE in 1985, and remediation efforts began in 1985.

Workers at the WSP received environmental doses during the operational period as a result of stack effluents from buildings, contamination of soil as a result of stack releases, and onsite storage of ore concentrates. Workers at the WSQ received environmental doses during the same period as a result of 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 the WSQ, the WSP, and the 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 the WSRP. For more information see ORAUT-TKBS-0028-2, *Weldon Spring Plant – Site Description* (ORAUT 2017b).

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 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 4.5.

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 4.4 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.

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, and their decay products. ORAUT-TKBS-0028-5, *Weldon Spring Plant – Occupational Internal Dose* (ORAUT 2017a) 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. The risks associated with ^{219}Rn, due to its extremely short half-life (4 seconds), were insignificant in comparison with those from ^{222}Rn and ^{220}Rn, and are not relevant. The same is true for the small amount of precursor radium due to the limited amount of ^{235}U WSP processed. Therefore, this TBD considers the inhalation intakes for ^{222}Rn and ^{220}Rn to be potentially significant, as discussed in more detail below.

4.2.2 Source Terms for Airborne Radionuclides

4.2.2.1 Operational Period, 1957 to 1966

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 2017b). 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 (Meshkov et al. 1986, pp. 47–48), assuming (1) 5,000 to 14,500 MT 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 an upper end estimate), (4) radon was in equilibrium with radium, and (5) all radon was released through the stack during processing.

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 the WSP. The discharge from the acid recovery plant was the primary source of radon emission.

Drums of yellowcake were emptied into the hopper at the top of the receiving and sampling building (ORAUT 2017b). 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. Impurities that were generated in the purification process before denitration were bled off in liquid form in the raffinate, which was pumped to the WSRP. 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) 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 Fernald and WSP effectively removed the radium but were not effective in removing thorium, specifically ^{230}Th. 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; Sears 1975, p. 143; Sears 1976, p. 4).

Impurities that were generated in the uranyl-nitrate purification process were bled off in the raffinate, which was also pumped to the WSRP. The raffinate contained a variety of radionuclides including thorium and radium (Author unknown, 1967, pp. 10–11). Wastes in the 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 Bechtel (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.

Wastes that were disposed of in the 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 the 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.

Recycled Uranium
The DR should assume as favorable to claimants that all of the uranium WSP processed after 1961 was recycled uranium (RU). This assumption is consistent with that in the *Ohio Field Office Recycled Uranium Recovery Project Report* (DOE 2000), which assumed in lieu of better information that all uranium receipts at WSP after 1961 were RU.

For the periods that include RU (i.e., after 1960), the DR should refer to ORAUT-TKBS-0017-5, *Feed Materials Production Center – Occupational Internal Dose* (ORAUT 2016) in relation to RU contaminant mass concentrations. Only the mass concentrations associated with the period from 1961 to 1972 as stated in Table 5-10 (ORAUT 2016) should be used because the plutonium out of specification in the tower ash (sent to Fernald from the Paducah Gaseous Diffusion Plant) was not sent to the WSP (ORAUT 2016, Section 5.3.2.3).

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 the WSP and WSQ beginning with 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. In addition, DRs should select the absorption type that yields the highest dose to the organ of interest. Calculated annual intakes are based on a 2,400-m^3/yr inhalation rate (ICRP 1994) using an hourly breathing rate of 1.2 m^3 for light activity and a 2,000-hour work year. Environmental intakes from ingestion are considered negligibly small. Intakes can be scaled to a different rate or to consider partial year exposures.

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 the average airborne particulate concentrations are presented in ORAUT-TKBS-0028-5 (ORAUT 2017a). 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 for an expanded discussion of the use of the special uranium microcurie at WSP. Other radionuclides were not measured.

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 concentration at two different locations of interest using the Pasquill-Gifford equation for Gaussian plume atmospheric dispersion:

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

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 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

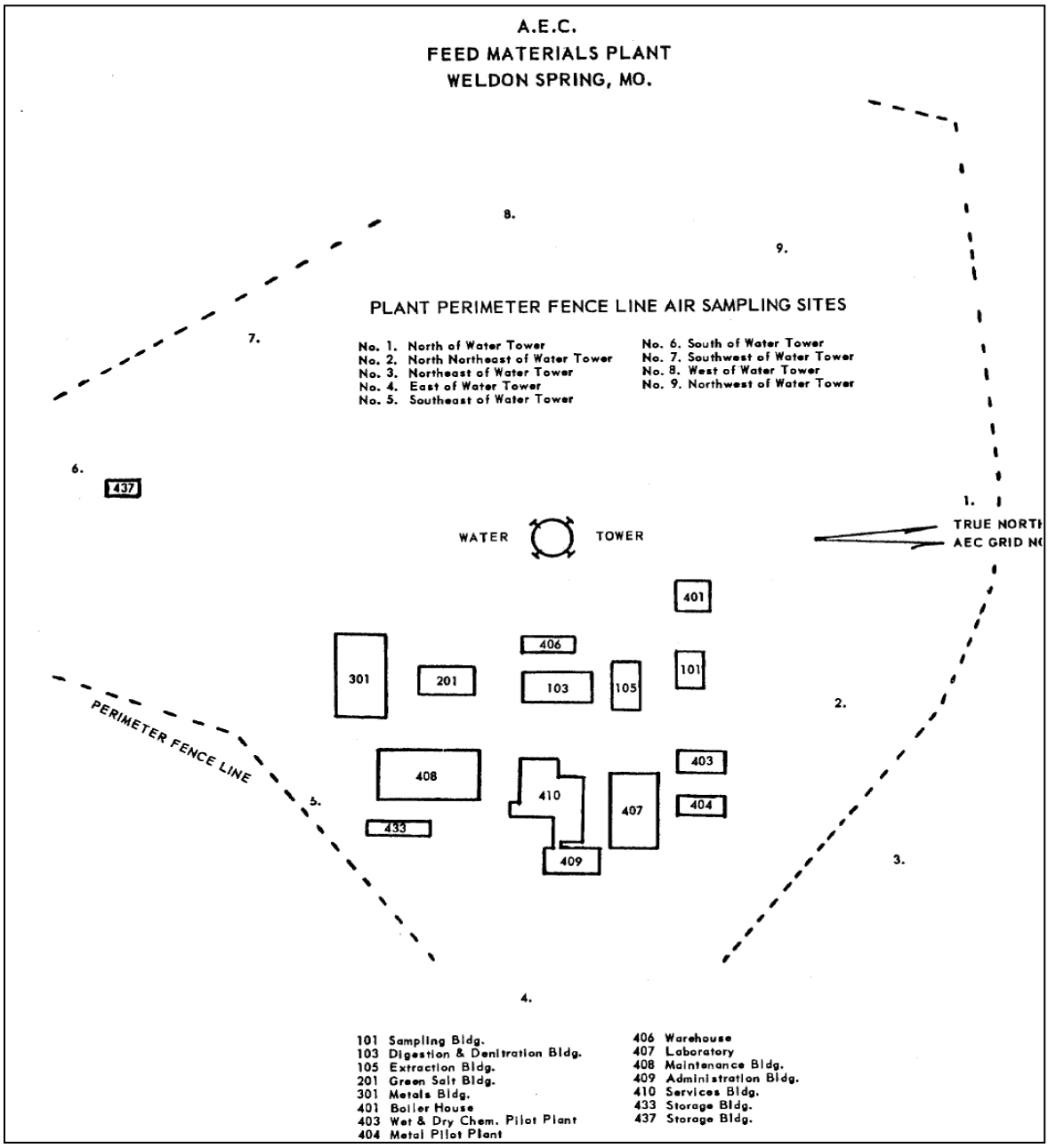

Figure 4-1. Perimeter sampling locations and processing facilities (lacking distance scale) (Source: Meshkov et al. 1986, p. 123).

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.

When Equation 4-1 is solved for 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.

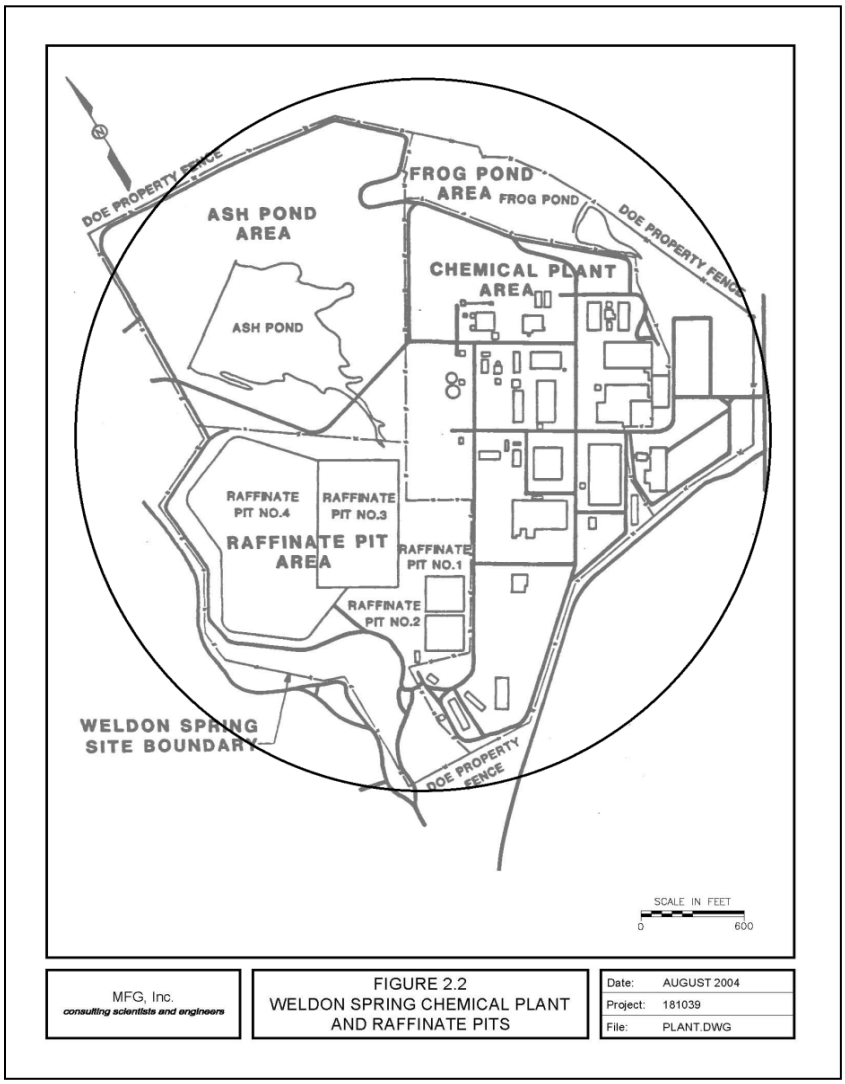

Figure 4-2. WSP and WSRP layout with superimposed 600-m radius circle to demonstrate the distance from the plant center to the perimeter.

Thorium intake, for those years when it was processed, can be estimated by scaling the annual uranium and thorium mass throughput rates 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.

The measured perimeter air concentration data for the 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. 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.

For 1957 and 1958 at the WSP, for which measurements are not available, this analysis assumed that perimeter air concentrations were the same as the measured concentrations in 1959, 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 2017b).

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 2017a), an annual ^{222}Rn intake of 12.4 WLM/yr 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.

A similar estimate for ^{220}Rn release from the WSP during the operational period was not made. Harris (1986, p. 86) states, “Natural thorium was typically received in either a nitrate or oxide form.” In addition, Harris (pp. 23, p. 28) indicates that the amount of processed thorium material ranged from a low of 0.05% of the processed natural uranium (NU) in 1964 to a high of 5.4% in 1965. Assuming concentrated thorium feed (i.e., 70% thorium) and secular equilibrium between ^{232}Th, ^{224}Ra, and ^{220}Rn, the ^{220}Rn release could approach 70% of the ^{222}Rn release. The estimated dose attributable to ^{220}Rn and its progeny is 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 (MK-Ferguson 2001a, pp. 31–35).

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 were reported in annual reports beginning with a monitoring report 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 the WSP (Bechtel 1986, pp. 34–35), which transferred back to DOE at that time. Air particulate monitoring was added beginning in 1987 at the WSP and WSRP (MK-Ferguson 1988, pp. 77–83) and beginning in 1989 at the WSQ (MK-Ferguson 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 the WSRP, WSP, and WSQ for periods after 1974.

Airborne Particulate Radionuclides

Airborne particulate results were reported at the WSP and WSRP beginning in 1987 and at the WSQ beginning in 1989 (MK-Ferguson 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).

ORAUT-TKBS-0028-5 (ORAUT 2017a) lists air monitoring data for airborne particulate radionuclides during the postoperational years. The data are reported as gross alpha rather than uranium. Because more than 99% of the material WSP received was NU, it is likely that the gross alpha data represents the NU concentration but may be assumed to be EU for dose calculation purposes. Figures 4-3 and 4-4 show the locations of monitoring stations for the WSRP and WSP and for the

WSQ, respectively. Radioactive air particulates were not monitored before the beginning of remediation activities at the site in 1985. In 1987 and 1988, monitoring of particulates at a few perimeter locations for the WSRP and WSP and in 1989 at the WSQ indicated that measured gross alpha concentrations were statistically indistinguishable from background (MK-Ferguson 1988, p. 81; 1989a, p. 92; and 1990a, p. 133). Therefore, the concentrations in 1987 and 1989 at the WSRP and WSP and in 1989 at the WSQ are zero. Because all areas of the WSP were essentially undisturbed between 1975 and the beginning of remediation activities in 1985, this analysis assumed that radioactive air particulate concentrations before 1987 were the same as those measured in 1987 through 1989. Therefore, ORAUT-TKBS-0028-5 lists particulate concentrations from 1975 through 1986 as insignificant.

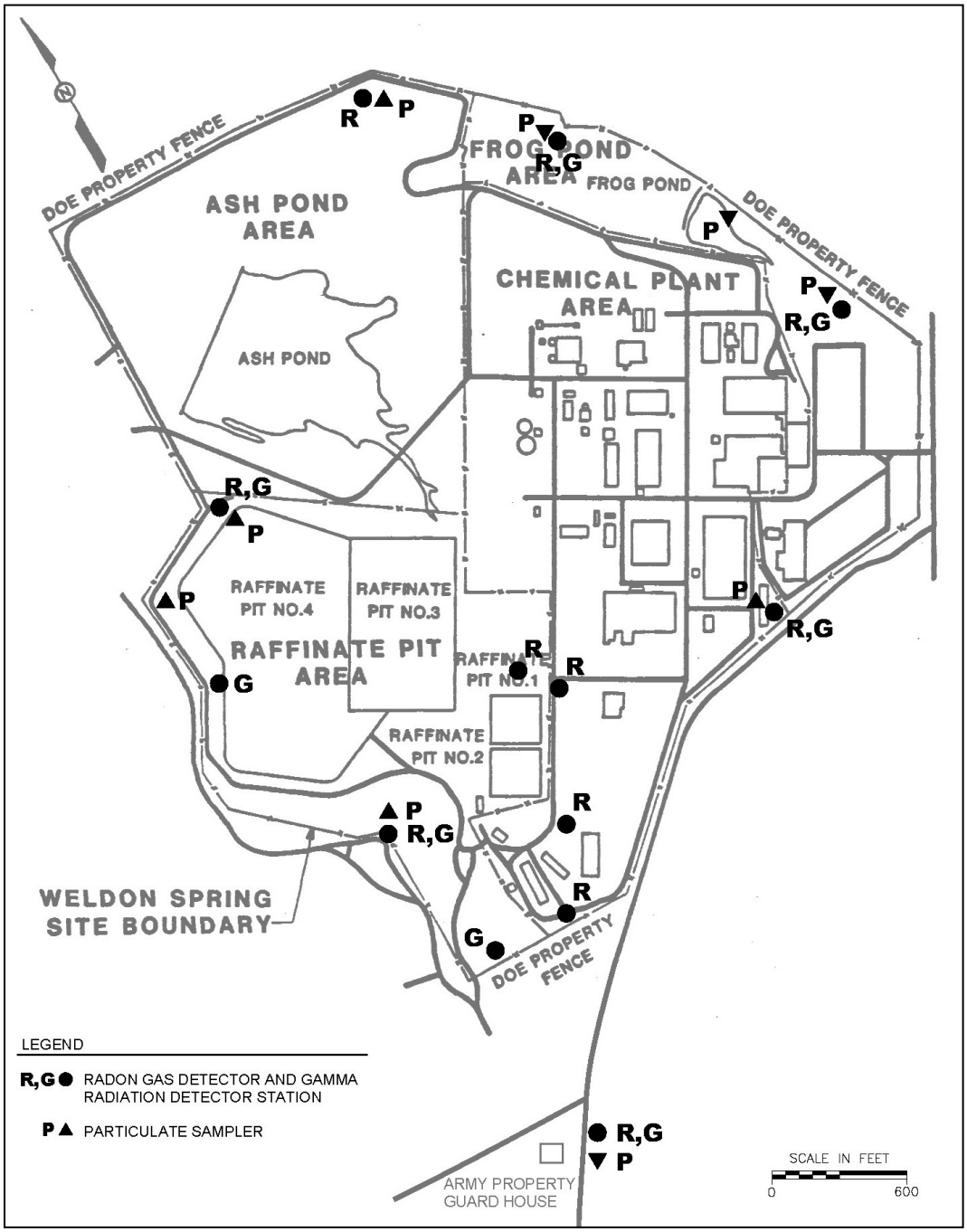

Figure 4-3. Air particulate (P), radon (R), and gamma (G) monitoring stations in WSP and WSRP.

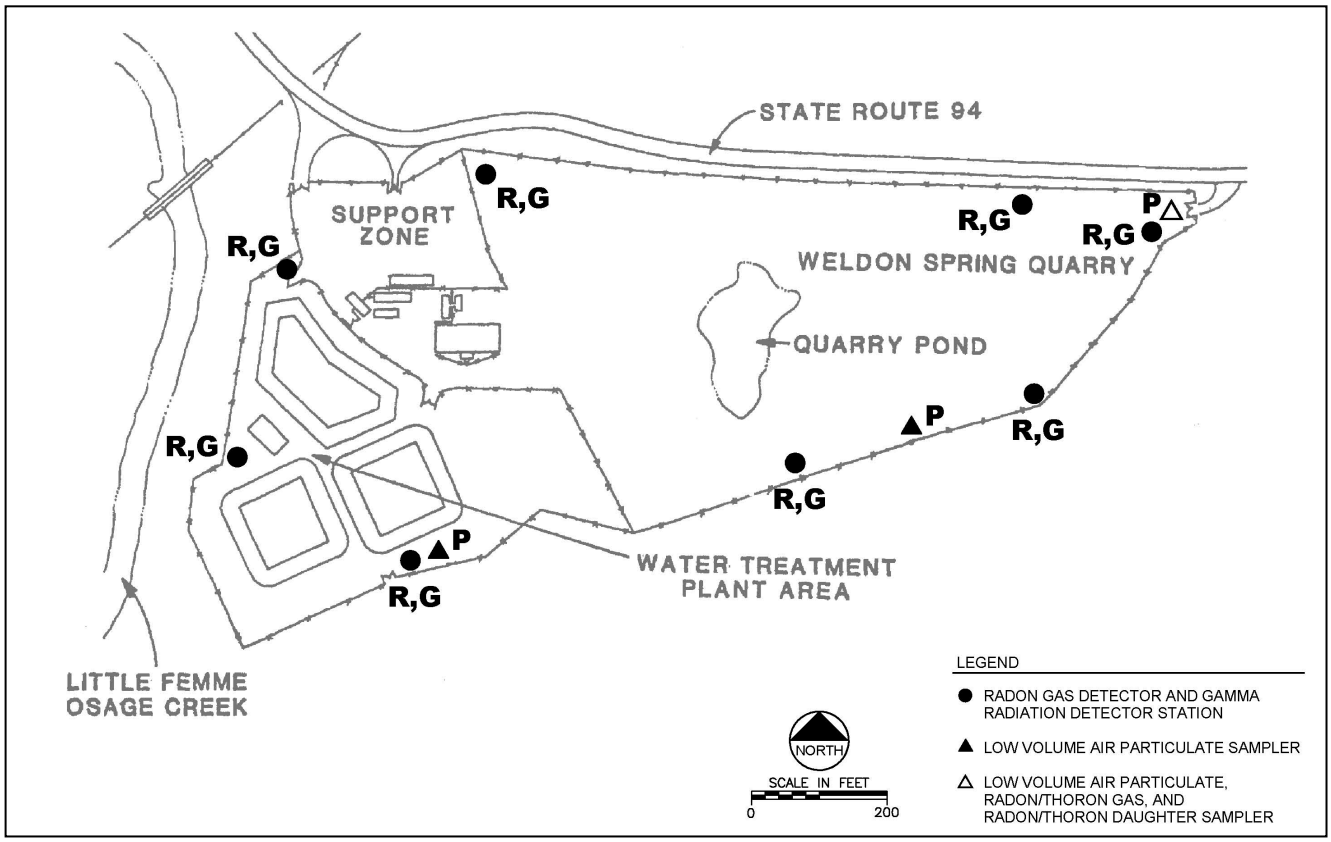

Figure 4-4. Air particulate (P), radon (R), and gamma (G) monitoring stations in WSQ.

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 the 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 in ORAUT-TKBS-0028-5 (ORAUT 2017a).

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 the 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 the WSP, WSRP, and WSQ, which is all that are available for air particulates, seldom showed air concentration measurements higher than those at offsite background monitoring stations. Some isotope-specific data appear in annual reports in the late 1990s but, because the ratio of isotopes probably would be highly variable by location due to the variability in isotopic composition of the contaminated soil, the utility of these data is limited.

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 (MK-Ferguson 2001b, pp. 95, 230–237; MK-Ferguson 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 within the Disposal Cell in 2001 (MK-Ferguson 2002, pp. 8 - 9), the intakes for 2001 were assumed to be equal to the intakes for 2000. The Weldon Spring Site Remediation Program was effectively complete in 2002.

The site has since been transferred for long-term surveillance and maintenance, and it is not covered under EEOICPA beyond 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 are zero beginning in 2002.

Table 4-2 lists the annual median intakes for each of the three WSP sites: WSP, WSRP, and WSQ. Table 4-3 lists the maximum sitewide median ^{234}U intakes for the remediation period. These intakes correspond to the highest value, by year, for the WSP, WSRP, and WSQ. The intakes were obtained by multiplying the ^{234}U concentrations (Bq/m^3) by an assumed inhalation rate of 2,400 m^3/yr (ORAUT 2013). The RU contaminant intake activities were calculated as stated in Section 4.2.4 by multiplying the uranium-234 value, either that stated in Table 4-2 or Table 4-3, by the ratio stated in Table 4-1.

Radon

Radon measurements in the 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.

During the postoperational years, outdoor radon was measured at the WSP, WSRP, and WSQ (Weidner and Boback 1982, pp. 28–30, 33, 50; Bechtel 1983a, pp. 22–25; 1983b, pp. 22-27; 1984a, pp. 23–26; 1985a, pp. 24–48; 1986, pp. 34–41; MK-Ferguson 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 the 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 within the Disposal Cell in 2001 (MK-Ferguson 2002, pp. 8 and 9), the intakes for 2001 were assumed to be equal to the intakes for 2000.

At the 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 WSP and 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 each of the two areas (WSP and WSRP). ORAUT-TKBS-0028-5 (ORAUT 2017a) 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.

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 the WSQ, radon measurements occurred only at the perimeter monitoring stations except in 1989, when monitors were placed inside the perimeter down to the quarry floor. The ratio of the average perimeter radon concentration to the average interior 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. This TBD assumes the radon concentration during this period of active remediation to be 30 times the concentration measured at the perimeter (ORAUT 2017a).

4.2.4 Radionuclide Intake Derivation

For the purposes of dose reconstruction, the assumption was made that all uranium processed at WSP was natural uranium from 1957 through 1962, with a specific activity 683 pCi/mg. After 1962, all uranium was assumed to be enriched to 1%, with a specific activity of 973 pCi/mg (ORAUT 2017a). Most of the RU at WSP came from the Feed Materials Production Center (FMPC, or Fernald), which in turn received most of their RU from the Hanford Site and was recycled from weapons grade plutonium. Therefore, a 6% weapons-grade mixture that had been chemically purified in 1961 was selected for dose calculations. 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 2017a). The following table states the RU contaminant intakes per unit activity of uranium.

Table 4-1. RU contaminant intakes per unit activity of uranium, Bq /Bq U (ORAUT 2017a).

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.

Table 4-2. Annual median intakes for WSP, WSRP, and WSQ.

Year	WSRP U-234[a] (Bq/yr)	WSRP radon[b] (WLM/yr)	WSP U-234 (Bq/yr)	WSP Th-230 (Bq/yr)	WSP natural Th (Bq/yr)	WSP radon[b] (WLM/yr)	WSQ U-234 (Bq/yr)	WSQ radon[b] (WLM/yr)
1957–1959	0.00E+00[c]	0.00E+00[c]	6.78E+02	5.43E+02	0.00E+00	1.24E+01[d]	0.00E+00[e]	0.00E+00[e]
1960	0.00E+00[c]	0.00E+00[c]	1.38E+03	1.11E+03	0.00E+00	1.24E+01[d]	0.00E+00[e]	0.00E+00[e]
1961	0.00E+00[c]	0.00E+00[c]	2.37E+03	1.90E+03	0.00E+00	1.24E+01[d]	3.47E+00	0.00E+00[e]
1962	0.00E+00[c]	0.00E+00[c]	5.85E+02	4.68E+02	0.00E+00	1.24E+01[d]	2.36E+00	0.00E+00[e]
1963	0.00E+00[c]	0.00E+00[c]	1.06E+03	8.49E+02	0.00E+00	1.24E+01[d]	2.56E+00	1.24E+01[d]
1964	0.00E+00[c]	0.00E+00[c]	8.11E+02	6.49E+02	6.28E–01	1.24E+01[d]	5.90E+00	1.24E+01[d]
1965	0.00E+00[c]	0.00E+00[c]	4.42E+02	3.54E+02	1.17E+01	1.24E+01[d]	3.93E+01	1.24E+01[d]
1966	0.00E+00[c]	0.00E+00[c]	4.42E+02	3.54E+02	3.82E+01	1.24E+01[d]	3.93E+01	1.24E+01[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[g]	0.00E+00[f]	0.00E+00[f]
1975–1976	0.00E+00[c]	4.06E–02	0.00E+00[g]	0.00E+00[g]	0.00E+00[g]	0.00E+00[g]	3.93E+01	1.90E–02
1977–1978	0.00E+00[c]	5.79E–02	0.00E+00[g]	0.00E+00[g]	0.00E+00[g]	0.00E+00[g]	3.93E+01	1.93E–02
1979	0.00E+00[c]	1.06E–02	0.00E+00[g]	0.00E+00[g]	0.00E+00[g]	0.00E+00[g]	3.93E+01	1.06E–02
1980	0.00E+00[c]	6.56E–02	0.00E+00[g]	0.00E+00[g]	0.00E+00[g]	0.00E+00[g]	3.93E+01	1.74E–02
1981	0.00E+00[c]	4.30E–02	0.00E+00[g]	0.00E+00[g]	0.00E+00[g]	0.00E+00[g]	3.93E+01	2.22E–02
1982	0.00E+00[c]	8.69E–03	0.00E+00[g]	0.00E+00[g]	0.00E+00[g]	0.00E+00[g]	3.93E+01	2.53E–02
1982	0.00E+00[c]	1.00E–02	0.00E+00[g]	0.00E+00[g]	0.00E+00[g]	0.00E+00[g]	3.93E+01	2.10E–02
1984	0.00E+00[c]	1.72E–02	0.00E+00[g]	0.00E+00[g]	0.00E+00[g]	0.00E+00[g]	3.93E+01	2.38E–02
1985	0.00E+00[c]	1.14E–02	3.28E+00	2.62E+00	0.00E+00[h]	2.15E–01	3.93E+01	2.38E–02
1986	0.00E+00[c]	1.62E–02	3.28E+00	2.62E+00	0.00E+00[h]	3.29E–01	3.93E+01	2.29E–02
1987	0.00E+00	1.34E–02	3.28E+00	2.62E+00	0.00E+00[h]	4.29E–01	3.93E+01	4.29E–02
1988	0.00E+00	2.10E–02	3.28E+00	2.62E+00	0.00E+00[h]	5.87E–01	0.00E+00	6.49E–02
1989	0.00E+00	1.57E–02	3.28E+00	2.62E+00	0.00E+00[h]	5.44E–01	0.00E+00	4.10E–02
1990	1.20E–01	9.54E–03	3.28E+00	2.62E+00	0.00E+00[h]	3.43E–01	0.00E+00	3.34E–02
1991	6.00E–02	1.05E–02	1.98E+00	1.58E+00	0.00E+00[h]	2.86E–01	0.00E+00	2.86E–02
1992	4.68E–02	1.05E–02	1.48E+00	1.18E+00	0.00E+00[h]	2.29E–01	0.00E+00	2.58E–02
1993	5.52E–02	4.77E–03	1.66E+00	1.32E+00	0.00E+00[h]	1.06E–01	0.00E+00	5.82E–02
1994	6.48E–02	1.34E–02	2.27E+00	1.81E+00	0.00E+00[h]	2.43E–01	0.00E+00	1.62E–01
1995	5.64E–02	1.62E–02	1.84E+00	1.47E+00	0.00E+00[h]	3.15E–01	0.00E+00	5.53E–02
1996	7.44E–02	2.72E–02	2.12E+00	1.70E+00	0.00E+00[h]	3.86E–01	0.00E+00	1.24E–02
1997	9.00E–02	6.20E–02	1.98E+00	1.58E+00	0.00E+00[h]	3.15E–01	0.00E+00	1.05E–02
1998	1.04E–01	1.10E–02	2.77E+00	2.22E+00	0.00E+00[h]	1.86E–01	0.00E+00	7.06E–03
1999	9.24E–02	1.76E–02	2.74E+00	2.19E+00	0.00E+00[h]	3.58E–01	0.00E+00	1.62E–02
2000	4.92E–02	9.54E–03	1.84E+00	1.47E+00	0.00E+00[h]	3.72E–01	0.00E+00	1.24E–02
2001	4.92E–02	9.54E–03	1.84E+00	1.47E+00	0.00E+00[h]	3.72E–01	0.00E+00	1.24E–02
2002	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00[h]	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 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 Weldon Spring Site.
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. NLO began environmental monitoring at the WSRP and WSQ in August 1975.
g. DOD control period.
h. No source term for natural thorium.

Table 4-3. Maximum sitewide (WSP, WSQ, and WSRP) annual median intakes.

Year	U-234[a] (Bq/yr)	Th-228 (Bq/yr)	Th-230 (Bq/yr)	Th-232 (Bq/yr)	Pu-239 (Bq/yr)	Pu-241 (Bq/yr)	Am-241 (Bq/yr)	Np-237 (Bq/yr)	Tc-99 (Bq/yr)	Ru-106 (Bq/yr)	Zr-95 (Bq/yr)	Nb-95 (Bq/yr)	Sr-90 (Bq/yr)	Radon[b] (WLM/yr)
1957–1959	6.78E+02	0.00E+00	5.43E+02	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	1.24E+01
1960	1.38E+03	0.00E+00	1.11E+03	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	1.24E+01
1961	2.37E+03	2.67E-03	1.90E+03	3.82E-03	2.77E+00	2.86E+01	1.84E-03	9.58E-01	3.54E+02	3.83E+02	5.74E+01	5.74E+01	1.53E+01	1.24E+01
1962	5.85E+02	6.60E-04	4.68E+02	9.42E-04	6.85E-01	7.06E+00	4.54E-04	2.36E-01	8.74E+01	9.44E+01	1.42E+01	1.42E+01	3.78E+00	1.24E+01
1963	1.06E+03	8.39E-04	8.49E+02	1.20E-03	8.70E-01	8.98E+00	5.77E-04	3.01E-01	1.11E+02	1.20E+02	1.80E+01	1.80E+01	4.80E+00	1.24E+01
1964	8.11E+02	6.28E-01	6.49E+02	6.28E-01[e]	6.66E-01	6.87E+00	4.42E-04	2.30E-01	8.50E+01	9.19E+01	1.38E+01	1.38E+01	3.68E+00	1.24E+01
1965	4.42E+02	1.17E+01	3.54E+02	1.17E+01[e]	3.63E-01	3.74E+00	2.41E-04	1.25E-01	4.63E+01	5.01E+01	7.51E+00	7.51E+00	2.00E+00	1.24E+01
1966	4.42E+02	3.82E+01	3.54E+02	3.82E+01[e]	3.60E-01	2.31E+00	4.72E-02	1.25E-01	4.63E+01	5.01E+01	7.51E+00	7.51E+00	2.00E+00	1.24E+01
1967–1974	0.00E+00[c]	0.00E+00	0.00E+00[c]	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[c]
1975	3.93E+01	3.11E-05	0.00E+00[d]	4.44E-05	3.20E-02	2.06E-01	4.20E-03	1.11E-02	4.12E+00	4.45E+00	6.68E-01	6.68E-01	1.78E-01	4.06E-02
1976	3.93E+01	3.11E-05	0.00E+00[d]	4.44E-05	3.17E-02	1.27E-01	6.70E-03	1.11E-02	4.12E+00	4.45E+00	6.68E-01	6.68E-01	1.78E-01	4.06E-02
1977	3.93E+01	3.11E-05	0.00E+00[d]	4.44E-05	3.17E-02	1.27E-01	6.70E-03	1.11E-02	4.12E+00	4.45E+00	6.68E-01	6.68E-01	1.78E-01	5.79E-02
1978	3.93E+01	3.11E-05	0.00E+00[d]	4.44E-05	3.17E-02	1.27E-01	6.70E-03	1.11E-02	4.12E+00	4.45E+00	6.68E-01	6.68E-01	1.78E-01	5.79E-02
1979	3.93E+01	3.11E-05	0.00E+00[d]	4.44E-05	3.17E-02	1.27E-01	6.70E-03	1.11E-02	4.12E+00	4.45E+00	6.68E-01	6.68E-01	1.78E-01	1.06E-02
1980	3.93E+01	3.11E-05	0.00E+00[d]	4.44E-05	3.17E-02	1.27E-01	6.70E-03	1.11E-02	4.12E+00	4.45E+00	6.68E-01	6.68E-01	1.78E-01	6.56E-02
1981	3.93E+01	3.11E-05	0.00E+00[d]	4.44E-05	3.17E-02	1.27E-01	6.70E-03	1.11E-02	4.12E+00	4.45E+00	6.68E-01	6.68E-01	1.78E-01	4.30E-02
1982	3.93E+01	3.11E-05	0.00E+00[d]	4.44E-05	3.17E-02	1.27E-01	6.70E-03	1.11E-02	4.12E+00	4.45E+00	6.68E-01	6.68E-01	1.78E-01	2.53E-02
1982	3.93E+01	3.11E-05	0.00E+00[d]	4.44E-05	3.17E-02	1.27E-01	6.70E-03	1.11E-02	4.12E+00	4.45E+00	6.68E-01	6.68E-01	1.78E-01	2.10E-02
1984	3.93E+01	3.11E-05	0.00E+00[d]	4.44E-05	3.17E-02	1.27E-01	6.70E-03	1.11E-02	4.12E+00	4.45E+00	6.68E-01	6.68E-01	1.78E-01	2.38E-02
1985	3.93E+01	3.11E-05	2.62E+00	4.44E-05	3.17E-02	1.27E-01	6.70E-03	1.11E-02	4.12E+00	4.45E+00	6.68E-01	6.68E-01	1.78E-01	2.15E-01
1986	3.93E+01	3.11E-05	2.62E+00	4.44E-05	3.15E-02	7.88E-02	8.20E-03	1.11E-02	4.12E+00	4.45E+00	6.68E-01	6.68E-01	1.78E-01	3.29E-01
1987	3.93E+01	3.11E-05	2.62E+00	4.44E-05	3.15E-02	7.88E-02	8.20E-03	1.11E-02	4.12E+00	4.45E+00	6.68E-01	6.68E-01	1.78E-01	4.29E-01
1988	3.28E+00	2.60E-06	2.62E+00	3.71E-06	2.63E-03	6.57E-03	6.84E-04	9.30E-04	3.44E-01	3.72E-01	5.57E-02	5.57E-02	1.49E-02	5.87E-01
1989	3.28E+00	2.60E-06	2.62E+00	3.71E-06	2.63E-03	6.57E-03	6.84E-04	9.30E-04	3.44E-01	3.72E-01	5.57E-02	5.57E-02	1.49E-02	5.44E-01
1990	3.28E+00	2.60E-06	2.62E+00	3.71E-06	2.63E-03	6.57E-03	6.84E-04	9.30E-04	3.44E-01	3.72E-01	5.57E-02	5.57E-02	1.49E-02	3.43E-01
1991	1.98E+00	1.57E-06	1.58E+00	2.24E-06	1.59E-03	3.97E-03	4.13E-04	5.62E-04	2.08E-01	2.24E-01	3.36E-02	3.36E-02	8.97E-03	2.86E-01
1992	1.48E+00	1.17E-06	1.18E+00	1.67E-06	1.19E-03	2.97E-03	3.09E-04	4.20E-04	1.55E-01	1.68E-01	2.52E-02	2.52E-02	6.71E-03	2.29E-01
1993	1.66E+00	1.31E-06	1.32E+00	1.88E-06	1.33E-03	3.33E-03	3.46E-04	4.71E-04	1.74E-01	1.88E-01	2.82E-02	2.82E-02	7.52E-03	1.06E-01
1994	2.27E+00	1.80E-06	1.81E+00	2.57E-06	1.82E-03	4.55E-03	4.74E-04	6.44E-04	2.38E-01	2.57E-01	3.86E-02	3.86E-02	1.03E-02	2.43E-01
1995	1.84E+00	1.46E-06	1.47E+00	2.08E-06	1.48E-03	3.69E-03	3.84E-04	5.22E-04	1.93E-01	2.08E-01	3.13E-02	3.13E-02	8.34E-03	3.15E-01
1996	2.12E+00	1.68E-06	1.70E+00	2.40E-06	1.70E-03	4.25E-03	4.42E-04	6.01E-04	2.22E-01	2.40E-01	3.60E-02	3.60E-02	9.61E-03	3.86E-01
1997	1.98E+00	1.57E-06	1.58E+00	2.24E-06	1.59E-03	3.97E-03	4.13E-04	5.62E-04	2.08E-01	2.24E-01	3.36E-02	3.36E-02	8.97E-03	3.15E-01
1998	2.77E+00	2.19E-06	2.22E+00	3.13E-06	2.22E-03	5.55E-03	5.78E-04	7.86E-04	2.90E-01	3.14E-01	4.71E-02	4.71E-02	1.26E-02	1.86E-01
1999	2.74E+00	2.17E-06	2.19E+00	3.10E-06	2.20E-03	5.49E-03	5.72E-04	7.77E-04	2.87E-01	3.10E-01	4.66E-02	4.66E-02	1.24E-02	3.58E-01
2000	1.84E+00	1.46E-06	1.47E+00	2.08E-06	1.48E-03	3.69E-03	3.84E-04	5.22E-04	1.93E-01	2.08E-01	3.13E-02	3.13E-02	8.34E-03	3.72E-01
2001	1.84E+00	1.46E-06	1.47E+00	2.08E-06	1.48E-03	3.69E-03	3.84E-04	5.22E-04	1.93E-01	2.08E-01	3.13E-02	3.13E-02	8.34E-03	3.72E-01
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	1.00E+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 and includes natural background contribution.
c. The WSP was not a covered facility under EEOICPA and there were no AEC contractors at the WSRP and 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.

The TBD analysis used Equation 4-2 to convert the radon concentrations into intake values for periods outside the operational period from 1957 through 1966. The WLM/yr intake per Bq/m^3 for ^{222}Rn was calculated as:

$$^{222}Rn\,\frac{WLM/yr}{Bq/m^3} = \frac{0.3 \times 2000}{3{,}700 \times 170} = 9.54 \times 10^{-4} \quad (4\text{-}2)$$

Table 4-2 lists the annual median radon intake values for the WSP, WSRP, and WSQ. Table 4-3 lists maximum sitewide median intakes across WSP to be represented in the Interactive RadioEpidemiological Program (IREP) as lognormal distributions with a geometric standard deviation of 3.

The purpose of Table 4-2 is to assign the WSP worker an estimate of annual intake for various radionuclides for the three areas. This table can also be used to determine environmental internal doses specific to the worker's work site. The values in Table 4-1 can be used with the uranium values in Table 4-2 to determine the RU contaminant activities associated with the three WSP areas (raffinate pits, chemical plant, quarry). The purpose of Table 4-3 is to give the DR the maximum median intake for a specific year for use in determining the worker's dose. Table 4-3 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 the WSP is 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 the WSRP and WSQ.

A 1975 aerial radiological survey of the WSP (Jobst 1976, p. 32) indicated that, for most of the areas, the normal terrestrial gamma exposure rate was 3 to 6 µR/hr at 1 m above ground level and the average cosmic exposure rate was approximately 4 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 the WSRP and the WSQ, which indicated the presence of manmade changes from the natural radioisotopes (NIOSH 2010b, pp. 61–62). Section 4.3.1 identifies ambient exposures during the operational period, and Section 4.3.2 provides ambient exposures during the postoperational years.

4.3.1 Operational Period, 1957 to 1966

Available documents do not contain monitoring data that describes the ambient exposure rate at the 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 the 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 the WSP has been discovered for the operational period, DRs should consider applying the 50th-percentile value of

the occupational external dose (Table 4-4) for monitored workers during the operational period as favorable to claimants. 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.

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

Year	50th-percentile gamma (mrem)[a]
1957	161
1958	81
1959	78
1960	126
1961	136
1962	139
1963	220
1964	187
1965	151
1966	123

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

4.3.2 Postoperational Years, 1967 to 2002

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

Between 1982 and 2000, ambient exposure was monitored using thermoluminescent dosimeters at many perimeter locations around the WSP, the WSRP, and the WSQ (Bechtel 1983a, pp. 26–27; 1984a, pp. 27–28; 1985a, pp. 28–30; 1986, pp. 40–44; MK-Ferguson 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 the WSP and the WSRP were monitored, but the results did not indicate a significant difference in exposure rate from the perimeter stations. Figures 4-3 and 4-4 show 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.

Ambient exposure rates in excess of natural background radiation exposure rates existed before remediation in areas close to waste in the 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 exposure rates from 116 to 164 µR/hr with decreasing levels from 11.8 to 31.8 µR/hr at approximately 1,000 ft from the pits.

These measurements represent terrestrial radiation only. The average cosmic exposure rate of 4µR/hr should be added to the isopleths to compute the total exposure rate for personnel within the site boundary (Jobst 1976, p. 32).

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 (Bechtel 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. A comparison of the average survey-based value (201 mrem/yr) to the average perimeter value in 1983 of 88 mrem/yr (Bechtel 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 4-5 represent twice the average perimeter values for 1984 through 2000 and are recommended for environmental dose reconstruction. From 2001 to 2002, after the completion of remediation of most of the WSP (MK-Ferguson 2001b, p.79), the measured dose rate result has not been factored. For 1975 through 1983, the value of 201 mrem/yr is the average survey value for 1982 to 1983 from Bechtel (1984b, p. 22) because it is considered the best value to use for those years.

Table 4-5. Estimated ambient onsite doses.[a]

Year	WSRP average (mrem/yr)[b]	WSP average (mrem/yr)[c]	WSQ average (mrem/yr)[d]	Background average (mrem/yr)
1957–1966	(e)	(e)	Not significant	69
1975–1981	201	(f)	97	69
1982	201	(f)	85	69
1983	201	(f)	95	72
1984	245	(f)	127	110
1985	228	199	123	114
1986	183	157	97	82
1987	139	145	95	78
1988	120	126	73	58
1989	131	140	81	64
1990	127	133	77	59
1991	140	150	84	67
1992	135	137	73	67
1993	116	125	67	56
1994	118	122	65	55
1995	144	140	66	62
1996	165	135	62	60
1997	186	135	61	66
1998	139	126	57	57
1999	123	124	55	55
2000–2001	63[g]	111[g]	48[g]	52
2002	0	0	0	0

a. Based on 8,760 hr/yr exposure; 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 4-3 or evaluate on a case-by-case basis. Workers assigned to these areas were monitored; ambient dose was accounted for as part of occupational dose.
f. WSP did not transfer to DOE until 1985.
g. Not monitored after 2000; assumed equal to average for 2000 for respective location.

A similar radiological survey of the 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 (Bechtel 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 the WSQ was "extremely difficult because of the rough terrain," and that "the area was densely vegetated" (Bechtel 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 4-5 are appropriate for estimating exposures except during the excavation period, which occurred during most of 1993, 1994, and 1995 (MK-Ferguson 1994, pp. 44–45; 1995, p. 48; 1996, pp. 50–51). For Table 4-5, the average value as presented in annual environmental reports is considered the best value for dose reconstruction.

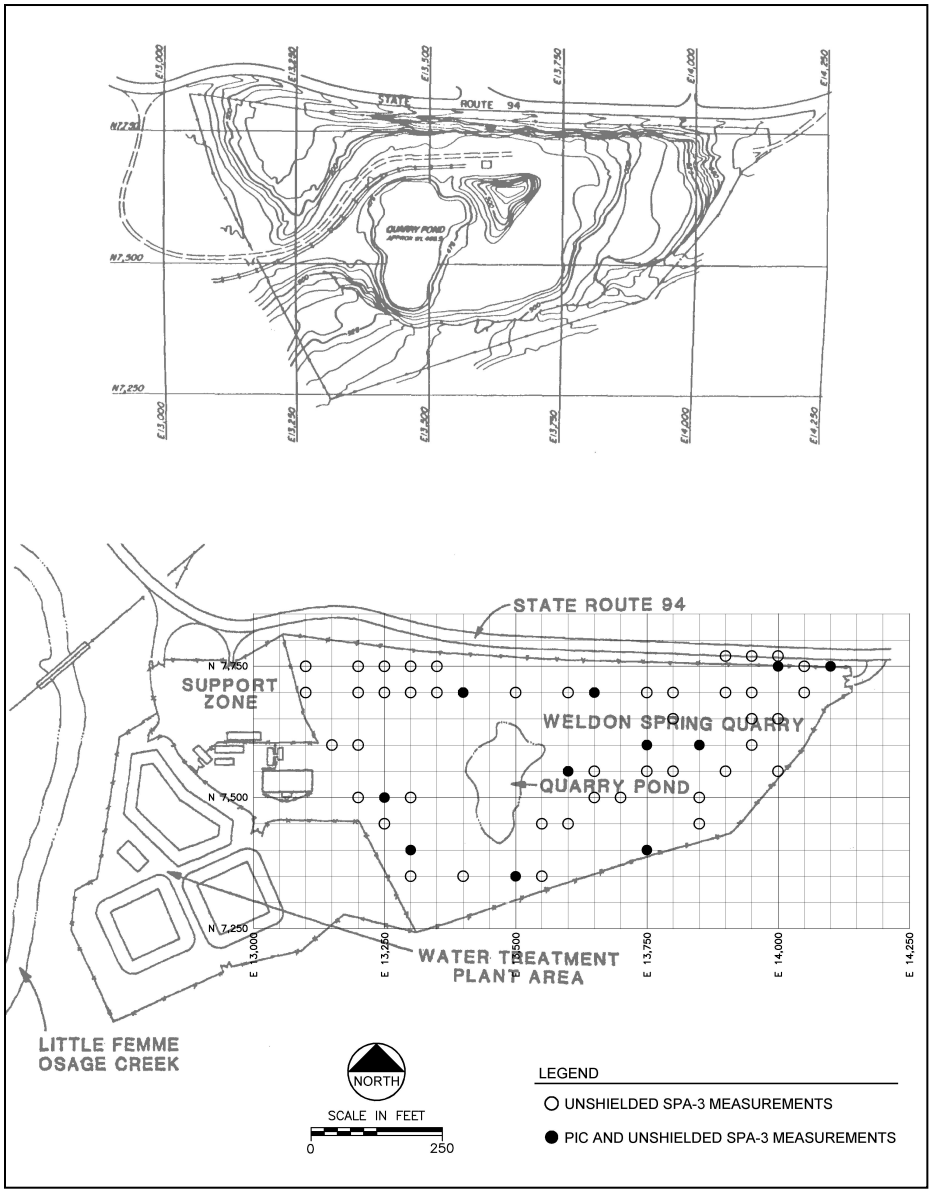

Figure 4-5. Topographic map and locations of gamma exposure rate measurements for WSQ (Bechtel 1985b, pp. 14, 17).

A 1987 radiologic characterization of the 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 the WSRP and WSP. Correlation of those counts with a pressurized ionization chamber allowed estimates of exposure rate in µR/hr. Exposure rates ranged from 9 to 287 µR/hr (at 1 m), which corresponds to a dose rate 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. Assuming 10% of the locations were at 85 µR/hr and the remaining 90% were at approximately 11 µR/hr produces an average exposure rate of approximately 18 µR/hr. This is a reasonable assumption for the WSP area 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 the WSP was essentially complete in 2000, the average onsite exposure rate was approximately twice the measured perimeter rate. Table 4-5 lists values reflecting this assumption.

Measured exposure rates are not available for 1975 through 1981 for the WSQ or for 1975 through 1982 for the WSRP. It is reasonably assumed that the average of the exposure rates from 1982 through 1989 for the WSQ and from 1983 through 1989 for the WSRP adequately represent these earlier years, when the entire site was essentially undisturbed. Table 4-5 lists these averaged rates. Table 4-6 lists sitewide maximum external exposure rates for WSP during the remediation period.

Table 4-6. Estimated maximum sitewide ambient dose at WSP.[a,b]

Year	Maximum for WSRP, WSP, and WSQ (mrem/yr)
1957–1966	(c)
1975–1983	201
1984	245
1985	228
1986	183
1987	145
1988	126
1989	140
1990	133
1991	150
1992	137
1993	125
1994	172
1995	144
1996	165
1997	186
1998	139
1999	124
2000–2001	111[d]
2002	0

a. Maximum of annual recommended average value for each area (from Table 4-4).
b. Based on 8,760-hr/yr exposure.
c. Apply the 50th-percentile occupational external dose from Table 4-3 or evaluate on a case-by-case basis.
d. Not monitored after 2000; assumed to be equal to the sitewide maximum for the WSP for 2000.

4.3.3 Organ Dose Conversion Factors

The measured photon dose is used with the dose conversion factors (DCFs) to calculate annual organ doses of interest using OCAS-IG-003, *External Dose Reconstruction Implementation Guideline* (NIOSH 2007), for an isotropic exposure geometry. For the operational period (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. For the period after 1983, the exposure (R)-to-organ DCF is used.

4.4 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 2016) in relation to the RU contaminants and their mass concentrations to be applied after 1960.

- Table 4-2 lists the annual median intake values for the WSP, WSRP, and WSQ.
- Table 4-3 lists maximum sitewide estimated median inhalation intakes of radioactive air particulates and radon.
- Table 4-4 lists the 50th-percentile values for external environmental dose for unmonitored workers during the operational period.
- Table 4-5 lists estimated average ambient onsite doses for WSRP, WSP, and WSQ.
- Table 4-6 provides the maximum sitewide estimates of ambient dose.

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.

4.5 ATTRIBUTIONS AND ANNOTATIONS

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

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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.

beta radiation
Charged particle emitted from some radioactive elements with a mass equal to 1/1,837 that of a proton. A negatively charged beta particle is identical to an electron. A positively charged beta particle is a positron.

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. See *acute exposure* and *chronic exposure*. (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.

gamma ray, particle, or photon
See gamma radiation.

ionizing radiation
Radiation of high enough energy to remove an electron from a struck atom and leave behind a positively charged ion. High enough doses of ionizing radiation can cause cellular damage. Ionizing particles include alpha particles, beta particles, gamma rays, X-rays, neutrons, high-speed electrons, high-speed protons, photoelectrons, Compton electrons, positron/negatron pairs from photon radiation, and scattered nuclei from fast neutrons. See *alpha radiation*, *beta radiation*, *gamma radiation*, *neutron radiation*, *photon radiation*, and *X-ray radiation*.

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. See *element*.

neutron radiation

Radiation that consists of free neutrons unattached to other subatomic particles emitted from a decaying radionuclide. Neutron radiation can cause further fission in fissionable material such as the chain reactions in nuclear reactors, and nonradioactive nuclides can become radioactive by absorbing free neutrons.

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.

photon radiation

Electromagnetic radiation that consists of quanta of energy (photons) from radiofrequency waves to gamma rays.

radiation

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

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 *radioactivity* and *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.

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.