ORAU TEAM
Dose Reconstruction Project for NIOSH

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DOE Review Release 02/14/2013

Document Title:	Document Number:	ORAUT-TKBS-0028-6
Weldon Spring Plant – Occupational External Dosimetry	Revision:	01
	Effective Date:	02/06/2013
	Type of Document:	TBD
	Supersedes:	Revision 00

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☐ New ☒ Total Rewrite ☐ Revision ☐ Page Change

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PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
06/24/2005	00	First approved issue of the technical basis document for the Weldon Spring Plant, Section 6, Occupational External Exposure. Incorporates formal internal and NIOSH review comments. Training is not required. Initiated by Robert Meyer.
02/06/2013	01	Revision to remove all surrogate data except the data from MCW. Added new material located since the last revision. Included a correction factor to account for worker-radiation source geometry to be applied to the measured and missed photon dose for operators, material handlers and trade workers to avoid an underestimate of dose. Organs most affected by this are those in the lower torso (stomach, pancreas, ovaries, etc.). DCAS-TIB-0013 was included as a reference and used to determine this geometric correction factor of 2.1. Revision incorporates responses and commitments based on SC&A and Advisory Board Working Group issues. 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

CFR Code of Federal Regulations
cm centimeter

DOE U.S. Department of Energy
DOELAP DOE Laboratory Accreditation Program

EEOICPA Energy Employees Occupational Illness Compensation Program Act

g gram

hr hour

keV kilovolt-electron, 1,000 electron volts

MCW Mallinckrodt Chemical Works
MDL minimum detectable level
MeV megavolt-electron, 1 million electron volts
mg milligram
mm millimeter
mR milliroentgen
mrem millirem
mrep millirep

NIOSH National Institute for Occupational Safety and Health

ORAU Oak Ridge Associated Universities

POC probability of causation

R roentgen

TBD technical basis document
TLD thermoluminescent dosimeter

U.S.C. United States Code

wk week
WSP Weldon Spring Plant

yr year

β beta

γ gamma

§ section or sections

6.1 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 sites or categories of sites. They will be revised in the event additional relevant information is obtained about the affected site(s). These documents may be used to assist NIOSH staff in the completion of the individual work required for each dose reconstruction.

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

For employees of DOE or its contractors with cancer, the DOE facility definition only determines eligibility for a dose reconstruction, which is a prerequisite to a compensation decision (except for members of the Special Exposure Cohort). The compensation decision for cancer claimants is based on a section of the statute entitled "Exposure in the Performance of Duty." That provision [42 U.S.C. § 7384n(b)] says that an individual with cancer "shall be determined to have sustained that cancer in the performance of duty for purposes of the compensation program if, and only if, the cancer … was at least as likely as not related to employment at the facility [where the employee worked], as determined in accordance with the POC [probability of causation[1]] guidelines established under subsection (c) …" [42 U.S.C. § 7384n(b)]. Neither the statute nor the probability of causation guidelines (nor the dose reconstruction regulation, 42 C.F.R. Pt. 82) restrict the "performance of duty" referred to in 42 U S. C. § 7384n(b) to nuclear weapons work (NIOSH 2010).

The statute also includes a definition of a DOE facility that excludes "buildings, structures, premises, grounds, or operations covered by Executive Order No. 12344, dated February 1, 1982 (42 U.S.C. 7158 note), pertaining to the Naval Nuclear Propulsion Program" [42 U.S.C. § 7384l(12)]. While this definition excludes Naval Nuclear Propulsion Facilities from being covered under the Act, the section of EEOICPA that deals with the compensation decision for covered employees with cancer [i.e., 42 U.S.C. § 7384n(b), entitled "Exposure in the Performance of Duty"] does not contain such an exclusion. Therefore, the statute requires NIOSH to include all occupationally-derived radiation exposures at covered facilities in its dose reconstructions for employees at DOE facilities, including radiation exposures related to the Naval Nuclear Propulsion Program. As a result, all internal and external occupational radiation exposures are considered valid for inclusion in a dose reconstruction. No efforts are made to determine the eligibility of any fraction of total measured exposure for inclusion in dose reconstruction. NIOSH, however, does not consider the following exposures to be occupationally derived (NIOSH 2010):

- 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

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1 The U.S. Department of Labor (DOL) is ultimately responsible under the EEOICPA for determining the POC.

6.1.1 Purpose

The purpose of this document is to describe Weldon Spring Plant (WSP) external dosimetry systems and practices.

6.1.2 Scope

WSP operations played an important role in the U.S. development of nuclear weapons through its processing of uranium and thorium from feed stocks to metal and intermediate products for use at other facilities. This TBD contains supporting documentation to assist in the evaluation of worker dose from WSP operations and processes. *External Dose Reconstruction Implementation Guideline* (NIOSH 2007) provides additional guidance.

The methods for radiation exposure measurement for workers have evolved since the beginning of WSP operations. An objective of this document is to provide supporting technical data to evaluate the external occupational dose that can reasonably be associated with WSP worker radiation exposure as covered under EEOICPA. The document addresses evaluation of unmonitored and monitored worker exposure as well as missed dose. In addition, to the extent possible with available data, it includes information on measurement uncertainties and describes how the uncertainties for WSP exposure and dose records are evaluated.

This TBD is one part of the WSP Site Profile. The Site Profile describes plant facilities and processes, historic information about occupational internal and external doses, and environmental data for use if recorded individual worker doses are unavailable. To the extent possible, this document provides necessary background information and critical data for the dose reconstructor to perform individual worker dose reconstructions. The guidance and requirements within this technical basis document pertain to covered employment periods for the Weldon Spring Site, which consists of the Weldon Spring Plant proper, or the Chemical Plant (1957 – July 1967; October 1985 – 2002), Weldon Spring Raffinate Pits (1957 – July 1967; December 1971 – 2002), and Weldon Spring Quarry (July 1960 – 2002). Site remediation at the Weldon Spring Plant proper conducted from January 1, 1968, through September 30, 1985, are not covered under EEOICPA.

6.2 DOSIMETRY OVERVIEW

With few exceptions, the WSP processed uranium during the operational period (1957–1966), but a small amount of thorium was processed near the end of the plant's operations (1963–1966). The *Technical Basis Document for the Weldon Spring Plant – Site Description* (ORAUT 2005a, p. 11) contains a chronology of thorium work. Table 6-1 lists the source terms of major concern. Figures 6-1 to 6-3 show complete decay chains of ^{238}U, ^{235}U, and ^{232}Th. Pa-234m is likely the most important contributor to skin dose because of its frequent high-energy beta emission. In addition, ^{234m}Pa emits higher energy gamma rays, albeit less frequently, than other nuclides of concern at WSP.

Table 6-1. Beta and gamma emissions of primary interest.[a]

Radionuclide	Beta energy (MeV, max.)	Gamma energy (MeV)
U-238	None	None
Th-234	0.10 (19%)	0.063 (3.5%)
	0.193 (79%)	0.093 (4%)
Pa-234m	2.28 (99%)	0.766 (0.2%)
		1.00 (0.6%)
U-235	None	0.144 (11%)
		0.163 (5%)
		0.186 (54%)
		0.205 (5%)
Th-231	0.205 (15%)	

	0.287 (49%)	0.026 (15%)
	0.304 (35%)	0.084 (6.5%)
U-234	None	0.053 (0.1%)

a. Source: Shleien, Slaback, and Birky (1998).

Actinium Series (4n + 3)*

Nuclide	Historical name	Half-life	Major radiation energies (MeV) and intensities† α	β	γ
$^{235}_{92}$U	Actinouranium	7.1 ×10^{8}y	4.37 (18%) 4.40 (57%) 4.58c‡ (8%)	---	0.143 (11%) 0.185 (54%) 0.204 (5%)
$^{231}_{90}$Th	Uranium Y	25.5h	---	0.140 (45%) 0.220 (15%) 0.305 (40%)	0.026 (2%) 0.084c (10%)
$^{231}_{91}$Pa	Protoactinium	3.25×10^{4}y	4.95 (22%) 5.01 (24%) 5.02 (23%)	---	0.027 (6%) 0.29c (6%)
$^{227}_{89}$Ac 98.6% 1.4%	Actinium	21.6y	4.86c (0.18%) 4.95c (1.2%)	0.043 (~99%)	0.070 (0.08%)
$^{227}_{90}$Th	Radioactinium	18.2d	5.76 (21%) 5.98 (24%) 6.04 (23%)	---	0.050 (8%) 0.237c (15%) 0.31c (8%)
$^{223}_{87}$Fr	Actinium K	22m	5.44 (~0.005%)	1.15 (~100%)	0.050 (40%) 0.080 (13%) 0.234 (4%)
$^{223}_{88}$Ra	Actinium X	11.43d	5.61 (26%) 5.71 (54%) 5.75 (9%)	---	0.149c (10%) 0.270 (10%) 0.33c (6%)
$^{219}_{86}$Rn	Emanation Actinon (An)	4.0s	6.42 (8%) 6.55 (11%) 6.82 (81%)	---	0.272 (9%) 0.401 (5%)
$^{215}_{84}$Po ~100% .00023%	Actinium A	1.78ms	7.38 (~100%)	0.74 (~.00023%)	---
$^{211}_{82}$Pb	Actinium B	36.1m	---	0.29 (1.4%) 0.56 (9.4%) 1.39 (87.5%)	0.405 (3.4%) 0.427 (1.8%) 0.832 (3.4%)
$^{215}_{85}$At	Astatine	~0.1ms	8.01 (~100%)	---	---
$^{211}_{83}$Bi 0.28% 99.7%	Actinium C	2.15m	6.28 (16%) 6.62 (84%)	0.60 (0.28%)	0.351 (14%)
$^{211}_{84}$Po	Actinium C'	0.52s	7.45 (99%)	---	0.570 (0.5%) 0.90 (0.5%)
$^{207}_{81}$Tl	Actinium C"	4.79m	---	1.44 (99.8%)	0.897 (0.16%)
$^{207}_{82}$Pb	Actinium D	Stable	---	---	---

*This expression describes the mass number of any member in this series, where *n* is an integer.
Example: $^{207}_{82}$Pb (4n + 3)......4(51) + 3 = 207
†Intensities refer to percentage of disintegrations of the nuclide itself, not to original parent of series.
‡Complex energy peak which would be incompletely resolved by instruments of moderately low resolving power such as scintillators.

Data taken from: Table of Isotopes and USNRDL-TR-802.

Figure 6-1. Uranium-235 decay series (HEW 1970).

Radiation protection practices and exposures at WSP varied over time. While no single documented description of the practices and processes were found, good descriptions of the film badge program were located (Author unknown undated) and other partial descriptions have been discerned from several documents as discussed in the following sections. Though contemporary references at WSP are limited, there is dose information for all years discussed.

Uranium Series (4n + 2)*

Nuclide	Historical name	Half-life	Major radiation energies (MeV) and intensities† α	β	γ
$^{238}_{92}U$	Uranium I	4.51×10^{9} y	4.15 (25%) 4.20 (75%)	---	---
$^{234}_{90}Th$	Uranium X_1	24.1d	---	0.103 (21%) 0.193 (79%)	0.063c‡ (3.5%) 0.093c (4%)
$^{234}_{91}Pa^{m}$ 99.87% / 0.13%	Uranium X_2	1.17m	---	2.29 (98%)	0.765 (0.30%) 1.001 (0.60%)
$^{234}_{91}Pa$	Uranium Z	6.75h	---	0.53 (66%) 1.13 (13%)	0.100 (50%) 0.70 (24%) 0.90 (70%)
$^{234}_{92}U$	Uranium II	2.47×10^{5} y	4.72 (28%) 4.77 (72%)	---	0.053 (0.2%)
$^{230}_{90}Th$	Ionium	8.0×10^{4} y	4.62 (24%) 4.68 (76%)	---	0.068 (0.6%) 0.142 (0.07%)
$^{226}_{88}Ra$	Radium	1602y	4.60 (6%) 4.78 (95%)	---	0.186 (4%)
$^{222}_{86}Rn$	Emanation Radon (Rn)	3.823d	5.49 (100%)	---	0.510 (0.07%)
$^{218}_{84}Po$ 99.98% / 0.02%	Radium A	3.05m	6.00 (~100%)	0.33 (~0.019%)	---
$^{214}_{82}Pb$	Radium B	26.8m	---	0.65 (50%) 0.71 (40%) 0.98 (6%)	0.295 (19%) 0.352 (36%)
$^{218}_{85}At$	Astatine	~2s	6.65 (6%) 6.70 (94%)	? (~0.1%)	---
$^{214}_{83}Bi$ 99.98% / 0.02%	Radium C	19.7m	5.45 (0.012%) 5.51 (0.008%)	1.0 (23%) 1.51 (40%) 3.26 (19%)	0.609 (47%) 1.120 (17%) 1.764 (17%)
$^{214}_{84}Po$	Radium C'	164μs	7.69 (100%)	---	0.799 (0.014%)
$^{210}_{81}Tl$	Radium C"	1.3m	---	1.3 (25%) 1.9 (56%) 2.3 (19%)	0.296 (80%) 0.795 (100%) 1.31 (21%)
$^{210}_{82}Pb$	Radium D	21y	3.72 (.000002%)	0.016 (85%) 0.061 (15%)	0.047 (4%)
$^{210}_{83}Bi$ ~100% / .00013%	Radium E	5.01d	4.65 (.00007%) 4.69 (.00005%)	1.161 (~100%)	---
$^{210}_{84}Po$	Radium F	138.4d	5.305 (100%)	---	0.803 (0.0011%)
$^{206}_{81}Tl$	Radium E"	4.19m	---	1.571 (100%)	---
$^{206}_{82}Pb$	Radium G	Stable	---	---	---

*This expression describes the mass number of any member in this series, where n is an integer.
Example: $^{206}_{82}Pb$ (4n + 2)......4(51) + 2 = 206
†Intensities refer to percentage of disintegrations of the nuclide itself, not to original parent of series.
‡Complex energy peak which would be incompletely resolved by instruments of moderately low resolving power such as scintillators.

Data taken from: Table of Isotopes and USNRDL-TR-802.

Figure 6-2. Uranium-238 decay series (HEW 1970).

Thorium Series (4n)*

Nuclide	Historical name	Half-life	Major radiation energies (MeV) and intensities† α	β	γ
$^{232}_{90}Th$	Thorium	1.41×10^{10}y	3.95 (24%) 4.01 (76%)	---	---
$^{228}_{88}Ra$	Mesothorium I	5.75y	---	0.055 (100%)	---
$^{228}_{89}Ac$	Mesothorium II	6.13h	---	1.18 (35%) 1.75 (12%) 2.09 (12%)	0.34c‡ (15%) 0.908 (25%) 0.96c (20%)
$^{228}_{90}Th$	Radiothorium	1.910y	5.34 (28%) 5.43 (71%)	---	0.084 (1.6%) 0.214 (0.3%)
$^{224}_{88}Ra$	Thorium X	3.64d	5.45 (6%) 5.68 (94%)	---	0.241 (3.7%)
$^{220}_{86}Rn$	Emanation Thoron (Tn)	55s	6.29 (100%)	---	0.55 (0.07%)
$^{216}_{84}Po$	Thorium A	0.15s	6.78 (100%)	---	---
$^{212}_{82}Pb$	Thorium B	10.64h	---	0.346 (81%) 0.586 (14%)	0.239 (47%) 0.300 (3.2%)
$^{212}_{83}Bi$ 64.0% 36.0%	Thorium C	60.6m	6.05 (25%) 6.09 (10%)	1.55 (5%) 2.26 (55%)	0.040 (2%) 0.727 (7%) 1.620 (1.8%)
$^{212}_{84}Po$	Thorium C'	304ns	8.78 (100%)	---	---
$^{208}_{81}Tl$	Thorium C"	3.10m	---	1.28 (25%) 1.52 (21%) 1.80 (50%)	0.511 (23%) 0.583 (86%) 0.860 (12%) 2.614 (100%)
$^{208}_{82}Pb$	Thorium D	Stable	---	---	---

*This expression describes the mass number of any member in this series, where n is an integer.
Example: $^{232}_{90}Th$ (4n)......4(58) = 232

†Intensities refer to percentage of disintegrations of the nuclide itself, not to original parent of series.

‡Complex energy peak which would be incompletely resolved by instruments of moderately low resolving power such as scintillators.

Data taken from: Lederer, C. M., Hollander, J. M., and Perlman, I., <u>Table of Isotopes</u> (6th ed.; New York: John Wiley & Sons, Inc., 1967) and Hogan, O. H., Zigman, P. E., and Mackin, J. L., <u>Beta Spectra</u> (USNRDL-TR-802 [Washington, D.C.: U.S. Atomic Energy Commission, 1964]).

Figure 6-3. Thorium-232 decay series (HEW 1970).

6.2.1 Plant Operations Period (1957 to 1966)

A film badge notification memorandum by the Mallinckrodt Chemical Works (MCW) Health and Safety Department (MCW 1958) indicates that the WSP film badge program began on March 1, 1958. Before that time, dosimetry at WSP was more than likely provided by the MCW St. Louis plant. A memo from Brandner to Mason (Brandner 1956a) states that some St. Louis employees transferred to the Weldon Spring Plant "where they are no longer being monitored for radiation exposure with film badges." This agrees with a footnote from individual film badge data summary sheets in 1966 that states, “during start-up at Weldon Spring in 1958 and later, some persons were not badged because [they were] not involved in radiation work” (an example is shown in Figure A-7 in Attachment A.)

Each employee, with the exception of “office females” (Brandner 1956a), wore a combination film badge and security badge. The film monitors were changed biweekly or more often as necessary. Burr (1959a) indicates that for turret lathe operators, film badges were exchanged weekly on Monday night. An undated report, *Film Badge Report 1958* (Author unknown circa 1958) indicates a biweekly exchange for dingot forge and chemical operators, but later states the badges were changed monthly. Burr (1959b) also states that “monthly exchange of film badges for all plant personnel is scheduled for January 30, 1959.” Another undated report, *Personnel External Radiation Monitoring Program* (MCW date unknown), describes the MCW program. It states that “wage personnel film badges are exchanged monthly and salaried personnel film badges quarterly.” A *Summary of Health Protection Practices* (MCW 1965) states that “operations badges are exchanged and processed on a calendar month schedule, all others [are exchanged] on a three-month schedule.” If the exchange frequency cannot be explicitly identified, the dose reconstructor should make the favorable-to-claimant assumption to use the most frequent exchange frequency for the period.

Brandner (1956b) describes the badges used at MCW as being manufactured by A. M. Samples Machine Company of Knoxville, Tennessee. The badge was of stainless-steel construction and held both security identification and radiation monitoring film. The front of the badge held the security and health identification information and was removable from the badge back; the front was shaped so that a 1-mm-thick cadmium shield could be inserted to cover approximately the top two-thirds of the film. A similar 1-mm cadmium shield was permanently clamped on the back of the badge. The film was DuPont dosimeter Type 552 film packets, which contained two dental-size films in a single wrapper. One of the films was apparently a DuPont Type 502 film and the other a DuPont Type 510 film. Brandner deemed the Type 502 film more sensitive than “most other films in the DuPont dosimeter series,” and three to four times as sensitive as the Eastman Type V-120 film. The net density (with density of the unexposed film deducted) of DuPont Type 502 film was “nearly proportional to the dose of any given type of radiation up to a density of 0.5 on a Welch Densichron.” This density supposedly corresponded to a dose of approximately 500 mR of 0.19-MeV gamma radiation or approximately 1,000 mrep of beta from aged uranium.

A 1965 document (MCW 1965) summarizes site health protection practices and has the following description of film badges in place at the time:

> *The standard dosimeter is a stainless-steel badge with clip, containing an open window to admit soft radiation and integral cadmium shields to exclude soft radiation; single film packet having a usable* [sic] *exposure range from 50 mr* [mR] *to 200 mr radium gamma. For work with enriched uranium, a special badge is used which incorporates multiple filters for differential determination of radiation energies.*

Personnel in operating areas of the plant and in some laboratories were required to wear badges continuously at work. In addition, permanent badges were assigned to those workers who frequently entered what were called “badged” areas. Spare badges were provided in available racks for those personnel who had a casual need to enter a badged area. Badges (dosimeters) were located in various process/work areas to provide reference data about changes in average radiation levels. Use of film badges by visitors or subcontract personnel was predetermined by the person who authorized entry and was managed on a self-prescribed basis (MCW 1958).

MCW (1965) also stated that “operations badges are exchanged and processed on a calendar [sic] month schedule, all others on a three-month schedule.” The term “operations badges” is assumed to refer to badges worn by personnel working in the operational, as opposed to administrative, sections of the plant. Ingle (1998) states that “film badge results were collected and read on a weekly basis until 1959 when the external program adopted a quarterly reading." The exception to this policy was the weekly exchange period for the turret lathe and dingot operators in the early period of operation (MCW 1956). Because of this confusion, it is suggested that if the exchange frequency cannot be determined from the claimant file, a favorable-to-claimant exchange frequency of biweekly be assumed for all operations workers, with the exception of the turret lathe and dingot operators, which would be weekly through 1958, and that an exchange frequency of monthly for production workers and quarterly for all other workers be assumed from 1959 to 1966.

Belcher (1966a) described monitoring for external radiation exposure as using a "stainless steel non-security badge containing a DuPont 555 film." This badge had a "useful range" of up to 10 R. Beta exposures were measured through the open-window (40 mg/cm^2) portion of the badge and were compared with a uranium beta calibration curve. Gamma exposures, primarily from uranium progeny and thorium, were measured under the cadmium shield and were compared with a radium gamma calibration. Mixed beta-gamma exposures were determined by subtraction.

6.2.2 Initial Cleanup Period (1967 to 1969)

Information has not been found that describes the external dosimetry program during the initial cleanup and shutdown phase following cessation of operations. There is some anecdotal information to indicate that some former WSP workers continued their employment during this period. That being the case, it is likely that the same film badge system would have been used and any dose received during this period would be in the claimant file.

Belcher (1966b) comments that "any new contractor operations on-site (maintenance, equipment removal, etc.) will need a minimum of health protection surveillance. … We do not feel such a contractor will need film badge services." However, it is not clear if this statement refers to a continued presence by MCW personnel.

6.2.3 Monitoring and Maintenance Period (1969 to 1985)

No information is currently available to describe the external dosimetry monitoring program for this period.

6.2.4 Site Remediation Period (1985 to 2000)

During the conduct of the Weldon Spring Site Remedial Action Project, the contractors, MK-Ferguson Company and Jacobs Engineering Group, provided personnel with whole-body thermoluminescent dosimeters (TLDs) for beta-gamma monitoring. These vendor-provided dosimeters (Landauer Alnor Type L-1) were capable of detecting deep and shallow doses to a minimum detection level of 10 mrem effective dose equivalent (DOE 1994). The dosimeter vendors were participants in the National Voluntary Laboratory Accreditation Program (DOE 2000).

From August 1992 to September 1994, during remediation, extremity doses were measured using ring dosimeters. The resultant data demonstrated that extremity dosimetry was not necessary for most work during the remediation period with the materials on the site at that time (DOE 2000).

6.3 DOSE RECONSTRUCTION PARAMETERS

6.3.1 Interpreting the External Dosimetry Record

Table 6-2 lists the process used to evaluate the measured film densities and to determine dose.

Table 6-2. Summary of historical recorded dose practices.[a]

Year	Dosimeter measured quantities	Compliance dose quantities
Two-element film (photon + electron)[b]		
Plant operations period 1957–1966	$SW_{density}$ $OW_{density}$ $OW_{density,beta} = OW_{density} - (G_{dose} \div CF_{OW,gamma})$	$G_{dose} = SW_{density} \times CF_{SW,gamma}$ $B_{dose} = OW_{density,beta} \times CF_{OW,beta}$
Plant operations period Special case for enriched uranium		
Maintenance period		
Landauer		
Site remediation period	(DOELAP Accredited)	

a. B_{dose} = beta dose (determined dose); CF =calibration factor determined from standard films (dose per unit density); G_{dose} = gamma dose (determined dose); $OW_{density}$ = open window (measured density); $OW_{density,\ beta}$ = open-window density resulting from beta exposure; $SW_{density}$ = shielded window (measured density).

b. Source: MCW (1956).

6.3.2 Weldon Spring Plant Historical Administrative Practices

The accuracy of the dosimetry system and recorded doses, and their comparability through time, depends on administrative practices based on technical, regulatory, and administrative requirements; dosimetry technologies and calibrations; process technologies; and training programs and practices.

As mentioned, the use of a dosimeter for production workers was always employed in one form or another at WSP. However, exposures have not always been determined for all employees. Female workers were not routinely monitored (Mason 1955), at least during the early history of the site. This could have been because it was presumed that they would not exceed 10% of the quarterly limit as defined by the U.S. Atomic Energy Commission (AEC).

6.3.2.1 Recorded Doses

WSP recorded both beta (skin) and gamma (deep) doses by determining film densities behind the open window and a single filter of approximately 1,000 mg/cm^2. Beta doses were recorded in units of millirep, and gamma doses in units of mR (mr on some reports). The rep is a historical unit (the word derives from *roentgen-equivalent-physical*), which variously equated to 83 to 95 ergs/g of tissue (Parker 1980). In 1956, the MCW Uranium Division considered converting to the rad for both gamma and beta dose (Brandner 1956c); however it appears that the conversion to rad was never accomplished. It is assumed that the 93-ergs/g rep was used throughout the WSP production years and it is favorable to claimants to assume that roentgens (R or r in the records), rep, and rem are all equivalent.

6.3.2.2 Discrepancies

If the employee’s record contains discrepancies, it is favorable to claimants to use the higher dose in the dose reconstruction. Care must be taken to interpret dose numbers properly if units were not specified. WSP routinely used milliroentgens or millirep as the unit of dose. Because of the tolerance limits in place at WSP, it is highly unlikely that a record would show a dose greater than the quarterly or annual limit without an additional record that indicated an overexposure. If no activity date is associated with a dose record, it is favorable to claimants to use that dose in the dose reconstruction. The dose reconstructor should use best judgment to credit the dose to the most likely year.

6.3.2.3 Missing Entry

A missing entry in the dosimetry history probably indicates that the individual missed the dosimeter exchange and that the next dosimeter includes the dose from both exchange periods. A less likely possibility is that the badge was lost and no dose was assigned for that period. The favorable-to-claimant assumption is that the dosimeter was lost, and dose should be assigned for that period using the dosimetry data from the previous and following periods, providing the job remained the same (consider the approach of Watson et al. 1994).

6.3.2.4 Badge Assignment and Exchange Frequency

Based on reviews of worker files, some individual dosimetry records are available, but the majority of results are quarterly totals. It is necessary to estimate the dosimeter exchange frequency from the available programmatic information. As described in several undated memoranda, personnel whose work routinely required them to be in a designated film badge area were assigned permanent film badges. “Office females” were not routinely assigned film badges. These data are found in Burr (1959c) and Mason (1955). Table 6-3 summarizes assignment of film badges during the operational period. Table 6-4 lists badge areas and nonbadge areas.

Table 6-3. Assignment of film badges.[a]

Permanent badges	All MCW Uranium Division wage (hourly) personnel are assigned permanent film badges.
	All MCW Uranium salaried personnel who regularly work in or routinely visit badge areas of the plant are assigned permanent film badges.
	Other non-MCW personnel, such as AEC, who regularly work in or routinely visit badge areas of the plant are assigned permanent film badges.
	All MCW Uranium Division personnel who work directly with enriched uranium materials are assigned special neutron dosimeter badges, which are worn in conjunction with the regular film badges.
Temporary film badges	Temporary film badges are provided for the use of other personnel (MCW visitors or otherwise) who do not normally work in badge areas but find it necessary to enter a badge area for a limited time.

a. Source: MCW (1958, p. 62).

Table 6-4. Badge and nonbadge areas.

Badge area	Nonbadge area
Sampling Plant	Administration Building
Refinery	Service Building
Green Salt Plant	Laboratories
Metal Plant	Maintenance Stores
Boiler house	Parking Lots
Warehouse	Water Plant
Pilot Plants	

Badges were picked up and returned at the end of the day by the individual. Wage personnel film badges were exchanged and processed, weekly, biweekly, and monthly, and salaried personnel film badges were exchanged and processed monthly and quarterly, with both dependent on the period as given in Section 6.2.1 above. Posting of individual film badge data to the employee’s health history file varied dependent on the exchange period, but the frequency was no greater than quarterly.

6.3.2.5 Interpretation of Reported Data

Table 6-5 summarizes several different formats in which health personnel recorded external dosimetry information for the WSP site. Many of the dosimetry reports did not specify the reporting units, but a June 16, 1956, memorandum from K. E. Brandner to J. W. Miller details the change from roentgen and rep to rad for both gamma and beta radiation (Brandner 1956c). The memorandum specifies that, beginning on June 18, 1956, units for both gamma and beta radiation “should be standardized to the ‘rad’ unit.” This memorandum predates the WSP site and is at odds with reports such as the Annual Personnel Internal-External Radiation Exposure Report shown in Figure A-3. It is favorable to claimants to assume that all units are rem. Figure A-7 shows a film badge summary report that includes data from multiple years.

Table 6-5. Interpretation of reported data.

Report	Reported quantity	Interpretation of zeroes	Interpretation of blanks (no data)
Personal Monitoring Summary Record (Figures A-1 - A-6) Typewritten summary of annual dosimetry record, including external and internal data.	Annual totals in mR or mrem. (Units are not noted.) External γ and β + γ reported by year for multiyear period. High quarters of β + γ are noted. Cumulative γ and β + γ are noted. Appear to be for early period of plant operation (1958–1962).	Zero indicates a monitored exposure reported as zero and should be treated as < MDL.	Blank indicates unmonitored during that period.
Film Badge Data Summary (Figures A-1 - A-6) Hand-generated summary of annual and cumulative external data. Typewritten form.	Annual totals in rad (γ) or rep (β). Gamma, β, and γ + β (rad) reported by year for multiyear period. Form begins in 1952 and has rows for each year through 1966. Form was designed to be used for Destrehan facility, WSP, and had notes for worker transfer to parent company with date noted.	Zero indicates a monitored exposure reported as zero and should be treated as < MDL.	Blank indicates unmonitored during that period. Notation on bottom of form indicates that "During start-up at Weldon Spring in 1958 and later, some persons were not badged because not involved in radiation work."
Annual Personnel Internal-External Radiation Exposure Report Health & Safety Dept. (Figure A-1)	For a single year, γ (mrem), β (mrem), and γ + β (mrem) are reported by quarter. Cumulative for previous year is also reported in same units. Number of weeks is also reported, but it appears that this number represents total number of weeks worked since initial employment. Internal radiation exposure is reported on same form.	Zero indicates a monitored exposure reported as zero and should be treated as < MDL.	Blank indicates unmonitored during that period.
Personnel Internal-External Radiation Summary 19xx-xx (Figure A-2) Computer-generated form for 2-yr period.	Quarterly data for γ and « γ / β. » No indication of units. Gamma/ β represents total external exposure for the period.	Zero indicates a monitored exposure reported as zero and should be treated as < MDL.	Blank indicates unmonitored during that period.
Annual Personnel Internal-External Radiation Exposure Report (Figure A-3) Computer-generated report analogous to typewritten report of same name.	For a single year, γ (mrem), β (mrem), and total, noted as « γ / β » (mrem) are reported by quarter. Cumulative for previous year is also reported in same units. Number of weeks is also reported, but it appears that this number represents total number of weeks worked since initial employment date, which is noted on printout. The weekly average external is also reported. Internal radiation exposure is reported on same form.	Zero indicates a monitored exposure reported as zero and should be treated as < MDL.	Blank indicates unmonitored during that period.
Annual Personal External Radiation Exposure Report Year		Zero indicates a monitored exposure reported	Blank indicates unmonitored during that period.

Report	Reported quantity	Interpretation of zeroes	Interpretation of blanks (no data)
19xx (Figure A-4) Computer-generated report.		as zero and should be treated as < MDL.	
Recorded External Exposure (Figure A-5) Computer-generated report showing both external and internal exposures by quarter. Have handwritten notations for external exposures by month for 1966.	Gamma and β and γ by year. Lifetime values for each. No indications of units, but presumably are mrem.	Zero indicates a monitored exposure reported as zero and should be treated as < MDL.	Blank indicates unmonitored during that period.
Quarterly External Radiation Exposure Report – Month 19xx (Figure A-6) Computer-generated list for a given month. Includes data for several workers on same sheet.	For month of the quarter, lists β and γ and γ alone. Units not specified, but presumed to be mrem. Month identified numerically. Year-to-date β and γ and γ values also given for each employee.	Zero indicates a monitored exposure reported as zero and should be treated as < MDL.	Blank indicates unmonitored during that period.

6.3.3 Plant-Wide Dosimetry Results

Available worker data were analyzed in an attempt to develop a profile of exposure for each type of job. Job titles reported in computer-assisted telephone interviews were utilized. As shown in Table 6-6, there were more than 70 different job titles for workers. These are categorized in nine categories that roughly represent the reported job titles. Table 6-7 lists the annual average gamma and beta exposures calculated for each category. Figures 6-4 and 6-5 show that the operator category received greater exposure to gamma rays in most years. Exposure to beta radiation was substantially greater for those in the operator category than for any other job category.

In the rare instance when a worker was unmonitored for external dose and should have been monitored based on his occupation and/or work location, the annual average gamma and beta dose values associated with the worker's occupation stated in Table 6-7 can be used to assign a reasonable estimate of dose. If a worker's occupation is unknown, the median dose values in Table 6-8 can be used to assign an unmonitored dose which is considered to be favorable to the claimant.

6.3.3.1 Calibration

The film badges used by MCW at the St. Louis site were calibrated using known exposures given to control films (Miller 1955). That same system was used at WSP. MCW (1965) states that:

> *Test and calibration dosimeters are exposed to radium gamma and to uranium beta. Density of personal dosimeter film is compared to the calibration film curves with results expressed in mr of gamma (radium equivalent) and mrep of beta (uranium equivalent). A direct conversion to mrad is assumed in recording personnel exposure.*

Table 6-6. Summary of job titles as reported by workers and coded for statistics.

Coded job title	Reported worker job titles
Equipment operator	Fork Lift Driver
	Fork Lift Operator
	Warehouse Fork Lift Operator
	Yard Operator
Foreman	Foreman
	Production Foreman
Manager	Accountant Supervisor
	Product Control Supervisor
	Supervisor, Plant and Maintenance Scheduler
Non-radiation job	Computer Operator
	Industrial Nurse
	Inventory Control Clerk
	Maintenance and Utility Control Clerk
	Office Boy/Accounting Clerk
	Shipping
Safety, security	Production/Safety and Fire Marshal
	Safety
	Safety and Fire Prevention
	Security Guard
Worker	Electrician
	General Cleaner
	Machinist
	Maintenance Electrician
	Maintenance & Oiler
	Maintenance Electrician
	Maintenance, Welder
	Maintenance/Rigger
	Metal Worker
	Millwright
	Pipefitter
	Tool and Die Maker
	Utility Worker
	Welder
	Welder, Maintenance
	Welder/Metal Fabricator

Coded job title	Reported worker job titles
Operator	Acid Recovery/Loader
	Chemical D95 Operator
	Chemical Operator, Storekeeper
	Chemical Operator Pot Room
	Chemical Operator
	Chemical Operator/Maintenance
	Conversion Green Salt
	Foreman-Operator
	Machine Operator
	Machinist, Operator
	Metal Plant, Manufacturer
	Operator
	Operator, Decontamination, Maintenance
	Operator/Labor
	Pot Room Worker
	Press Operator Refinery 103
	Processing Plant
	Production
	Production Operator
	Production Operator A
	Refinery Operator
	Uranium Processor
	Utility Operator
	Water Plant, Refinery
Engineer	Chemical and Project Engineer
	Chemical Engineer
	Engineer and Production Control
	Mechanical Engineer
	Plant Engineer
	Process Engineer
Laboratory worker	Analytical Chemist
	Chemical Technician
	Laboratory Technician
	Laboratory Technician, Engineer
	Research Chemist

6.3.4 Workplace Radiation Fields

No data were found that describe the workplace radiation fields at WSP. Summary reports indicate that natural uranium was the material the workers came in contact with most frequently. Radiation fields most often consisted of a complex mixture of beta and gamma energies. By reviewing personal dosimetry records, the dose reconstructor should be able to determine the relative magnitudes of each type of exposure. In many cases, the majority of the exposure would have consisted of beta particles, which can deliver substantial doses to bare skin relatively close to the source, but these particles do not penetrate deeply into the body.

6.3.4.1 Gamma Dose

No data have been found to indicate the gamma spectra in WSP work areas. However, nearly all the material processed at WSP was natural uranium, with small amounts of slightly enriched (< 1%), and

Table 6-7. Annual average gamma and beta dose (mR).

Job description	Annual average gamma exposure by year									
	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966
Engineer	116	102	60	164	106	143	148	330	195	94
Equipment operator	135	—	135	168	154	151	176	148	164	278
Foreman	361	80	134	181	171	176	132	143	171	113
Laboratory worker	280	78	70	74	130	176	203	255	531	155
Manager	52	—	37	517	102	41	142	112	78	64
Nonradiation job	114	—	48	90	94	72	93	226	198	33
Operator	298	122	159	250	402	383	648	533	417	295
Safety, security	168	75	265	59	65	83	415	273	119	183
Worker	240	132	70	150	189	257	400	370	279	195
Job description	**Annual average beta exposure by year**									
	1957	**1958**	**1959**	**1960**	**1961**	**1962**	**1963**	**1964**	**1965**	**1966**
Engineer	250	23	203	605	513	561	239	288	181	60
Equipment operator	190	344	1,167	835	800	668	324	430	338	171
Foreman	368	118	476	1,342	794	931	1,199	633	561	242
Laboratory worker	549	143	328	449	885	904	342	318	289	278
Manager	107	35	199	1,160	1,099	403	204	128	91	181
Nonradiation job	145	135	108	351	541	182	224	243	134	34
Operator	730	247	1,160	2,828	2,908	1,722	1,541	1,157	874	287
Safety, security	198	60	94	170	301	463	107	98	197	91
Worker	697	93	514	1,216	1,440	1,326	1,113	549	724	354

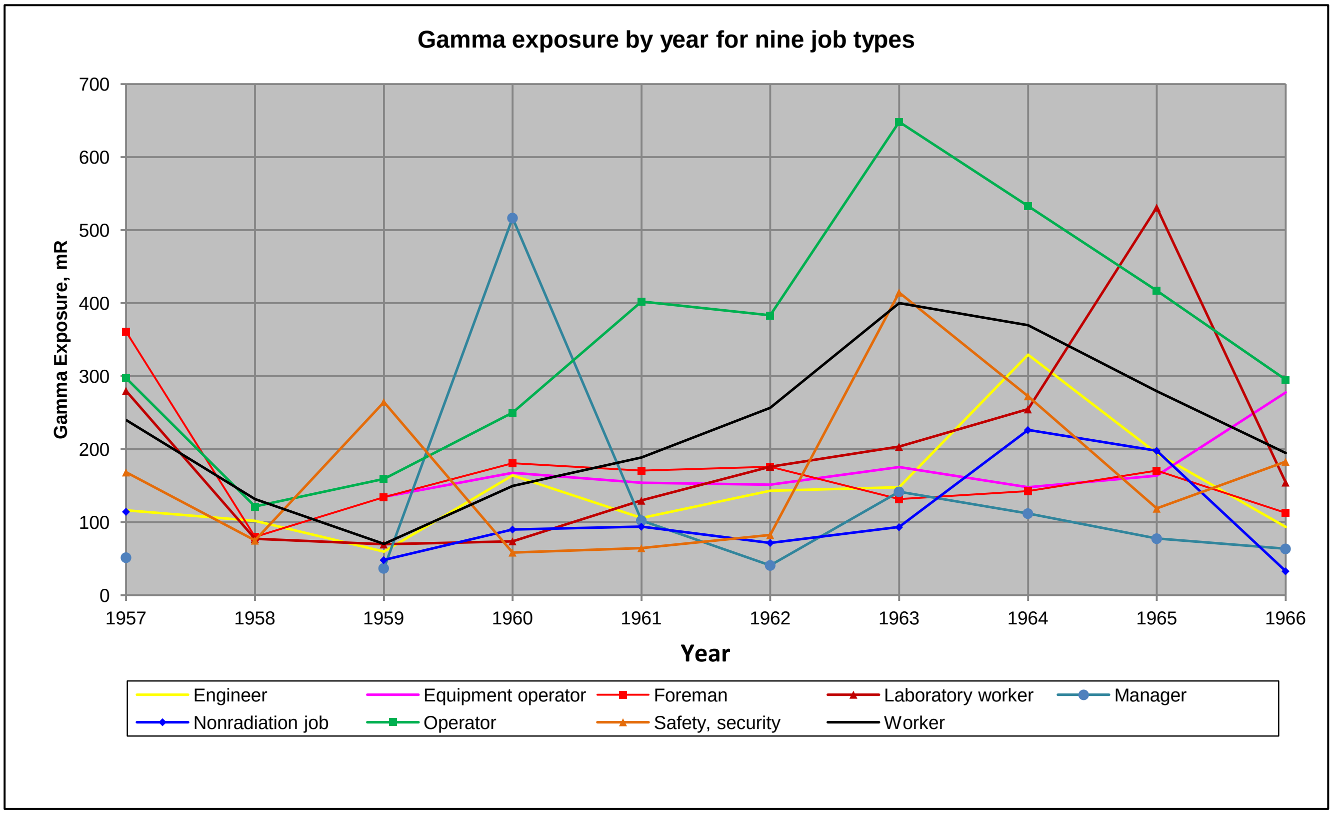

Figure 6-4. Average annual gamma exposure for various job categories.

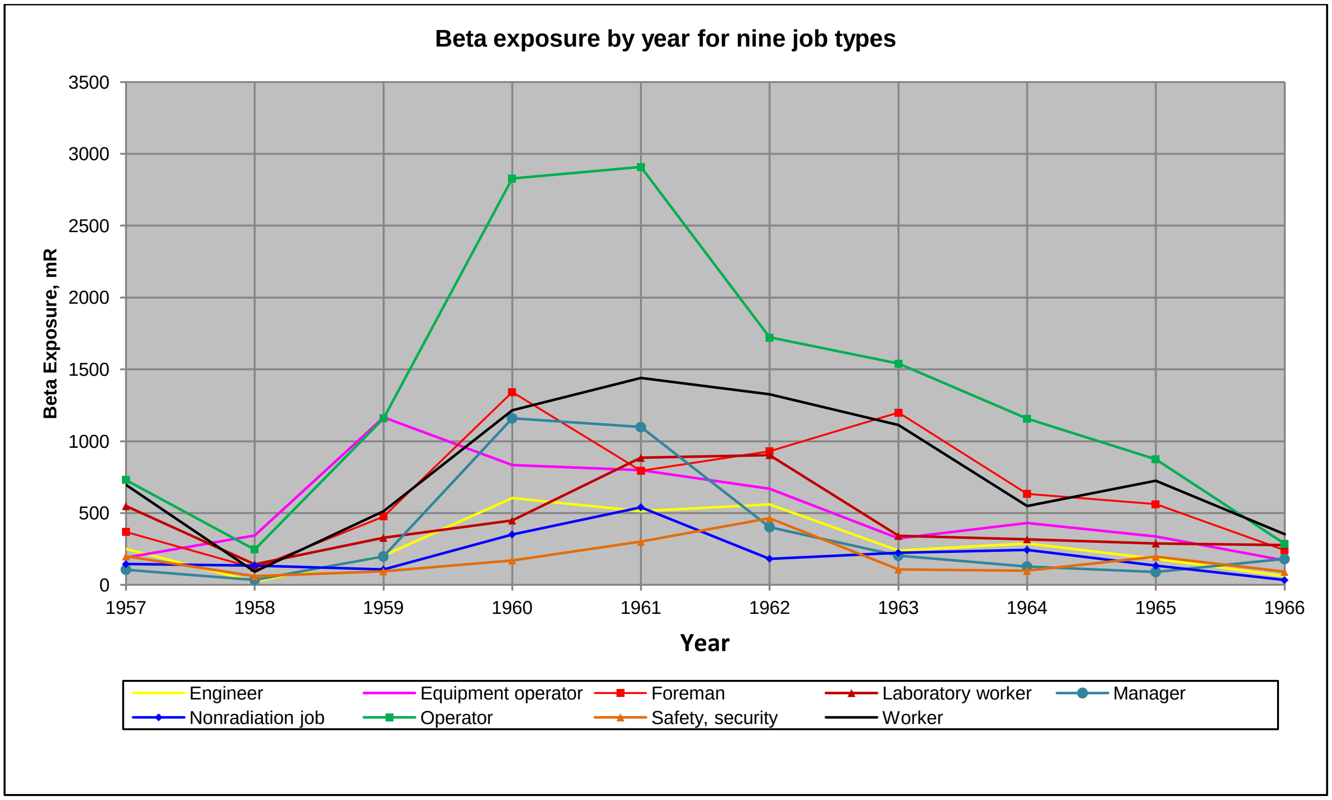

Figure 6-5. Average annual beta exposure for various job categories.

Table 6-8. Median values for occupational external dose through the operational period 1957-1966.[a]

Year	50th-percentile gamma (mrem)[b]	50th-percentile beta (mrem)
1957	161	305
1958	81	116
1959	78	317
1960	126	679
1961	136	859
1962	139	735
1963	220	314
1964	187	293
1965	151	226
1966	123	114

a. These annual dose values represent the median dose across all worker categories stated above in Table 6-7.

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

depleted uranium. It appears from the records that depleted and enriched uranium were routinely handled with some shielding, but the type and amounts of shielding are not now known. Enriched and depleted uranium are assumed to have been relatively fresh with little or no ingrowth of decay products having occurred at the time the material was processed at WSP.

However, ^{234m}Pa is a decay product in the ^{238}U decay chain and emits a 2.29-MeV beta particle. Therefore, there are a significant number of photons from bremsstrahlung, and they contribute photons of intermediate energy (30 to 250 keV). Bremsstrahlung radiation can contribute up to 40% of the photon dose from uranium metal (DOE 2009, p. 155). This decay product grows in fairly rapidly and is present in equilibrium quantities for most depleted uranium that was processed at WSP. It is appropriate to use the default assumption for depleted uranium that 50% of the dose is contributed by photons in the 30-to-50-keV photon energy range and 50% of the dose is a result of exposure from photons in the above-250-keV range.

Although enriched uranium has significantly less ingrowth of ^{234m}Pa, ^{235}U and its decay products emit a 185.7-keV photon 57% of the time and a 143.8-keV photon 11% of the time. These photons dominate the measured photon energy spectra. Therefore, for enriched uranium, it is appropriate and favorable to claimants to use the default assumption that the entire photon dose is a result of exposure in the 30-to-250-keV photon energy range. Table 6-9 shows the default assumptions. Table 6-10 lists energy distributions for WSP buildings.

Table 6-9. Default photon energy distribution for WSP materials.

Energy	Natural uranium	Depleted uranium	Slightly enriched uranium	Natural thorium
<30 keV	0%	0%	0%	0%
30-250 keV	50%	50%	100%	25%
>250 keV	50%	50%	0%	75%

Table 6-10. Energy distribution by building or area.

Building	Description	Radiation	Energy	Percentage
101	Sampling Plant	Natural U		
		Electron	>15 keV	100
		Photon	30–250 keV	50
			>250 keV	50
Area 102 A&B	Refinery Tank Farm	Natural U		
		Electron	>15 keV	100
		Photon	30–250 keV	50
			>250 keV	50
103	Digestion and Denitration	Natural U		
		Electron	>15 keV	100
		Photon	30–250 keV	50
			>250 keV	50
		Natural Th		
		Electron	>15 keV	100
		Photon	30–250 keV	25
			>250 keV	75
		Slightly enriched U		
		Electron	>15 keV	100
		Photon	30–250 keV	100
104	Lime Storage	None		
105	Extraction	Natural U		
		Electron	>15 keV	100
		Photon	30–250 keV	50
			>250 keV	50
		Natural Th		
		Electron	>15 keV	100
		Photon	30–250 keV	25
			>250 keV	75
		Slightly enriched U		
		Electron	>15 keV	100
		Photon	30–250 keV	100
106	Refinery sewer sampling	Natural U		
		Electron	>15 keV	100
		Photon	30–250 keV	50

Building	Description	Radiation	Energy	Percentage
			>250 keV	50
108	Nitric acid plant	Natural U		
		Electron	>15 keV	100
		Photon	30–250 keV	50
			>250 keV	50
109, 110	West Drum Storage, East Drum Storage	Natural U		
		Electron	>15 keV	100
		Photon	30–250 keV	50
			>250 keV	50
201	Green Salt Building	Natural U		
		Electron	>15 keV	100
		Photon	30–250 keV	50
			>250 keV	50
		Neutron	0.1–2 MeV	100
		Natural Th		
		Electron	>15 keV	100
		Photon	30–250 keV	25
			>250 keV	75
		Slightly enriched U		
		Electron	>15 keV	100
		Photon	30 – 250 keV	100
301	Metals Building	Natural U		
		Electron	>15 keV	100
		Photon	30 – 250 keV	50
			>250 keV	50
		Neutron	0.1 – 2 MeV	100
		Natural Th		
		Electron	>15 keV	100
		Photon	30 – 250 keV	25
			>250 keV	75
		Slightly enriched U		
		Electron	>15 keV	100
		Photon	30 – 250 keV	100
302	Magnesium Building	None		
Pad 303	Material Storage Pad	None		
401	Steam Plant	None		
403	Chemical Pilot Plant	Natural U		
		Electron	>15 keV	100
		Photon	30 – 250 keV	50
			>250 keV	50
		Depleted U		
		Electron	>15 keV	100
		Photon	30 – 250 keV	40
			>250 keV	60
404	Metallurgical Pilot Plant	Natural U		
		Electron	>15 keV	100
		Photon	30 – 250 keV	50
			>250 keV	50
		Depleted U		
		Electron	>15 keV	100
		Photon	30 – 250 keV	40
			>250 keV	60
405A & B	Pilot Plant Maintenance	Natural U		
		Electron	>15 keV	100
		Photon	30 – 250 keV	50

Building	Description	Radiation	Energy	Percentage
			>250 keV	50
406	Warehouse	Natural Th		
		Electron Photon	>15 keV 30 – 250 keV >250 keV	100 25 75
407	Laboratory	Natural U		
		Electron Photon	>15 keV 30–250 keV >250 keV	100 50 50
408	Maintenance and Stores	None		
409	Administration	None		
410	Services Building	None		
412	Electrical Substation	None		
413	Cooling Tower and Pump House	None		
414	Salvage Building	Natural U		
		Electron Photon	>15 keV 30–250 keV >250 keV	100 50 50
415	Process Incinerator	Natural U		
		Electron Photon	>15 keV 30–250 keV >250 keV	100 50 50
417	Paint Shop	None		
426	Water Tower	None		
427	Primary Sewage Treatment Plant	None		
428	Fuel Gas Plant	None		
429	Water Reserve Facilities	None		
430	Ambulance Garage	None		
43l	Laboratory Sewer Sampler	Natural U		
		Electron Photon	>15 keV 30–250 keV >250 keV	100 50 50
432	Main Sewer Sampler	None		
437	Records Retention Building	None		
439, 443	Fire Training and Storage Building	None		
441	Cylinder Storage	None		
202 A&B	Green Salt Tank Farm	None		

6.3.4.2 Neutron Dose

Because the WSP processed very small amounts of slightly enriched uranium (<1% ^{235}U and 0.68% of total throughput and no UF_6), the exposure to neutrons was miniscule (ORAUT 2010a, p. 33). The fact that the uranium was in the form of UF_4 and other nonproducing neutron compounds resulted in the total absence of recordable neutron doses even though neutron dosimeters were worn by those employees working with the enriched uranium (Author unknown undated). The slightly enriched uranium was processed in Buildings 103,105, 201, and 301, so employees assigned to these facilities during the processing of this material received neutron dosimeters. Studies as reported in ORAUT 2010a (p. 33 and pp. 59-61) provide adequate evidence that there is no technical reason to expect any measurable neutron doses and, therefore, no reported results.

Although no neutrons were anticipated or measured with the WSP film badge, it is possible that neutrons from the alpha-neutron reaction from UF_4 could have contributed dose to WSP workers. The analysis performed for the similar situation at Fernald (ORAUT 2004) is appropriate and will be used here.

Using the results of gamma and neutron dose rate measurements performed on depleted and low-enriched UF_4 drums, a neutron-to-gamma ratio was developed. The results of this analysis were that a neutron-to-gamma ratio of 0.1, lognormally distributed with a geometric standard deviation of 1.71 and a 95th percentile ratio of 0.23, should be applied in those areas where there is the potential for neutron dose from uranium fluoride compounds (ORAUT 2004, p. 20; NIOSH 2011a, p. 97).

6.3.4.3 Electron Dose

Beta radiation fields are usually the dominant external radiation hazard in facilities that involve contact work with unshielded forms of uranium. This was the case at WSP for natural and depleted uranium work. The most common exposure at WSP was to natural uranium, but depleted uranium [0.14% of total mass (ORAUT 2010a, p. 23)] was also present at the site on an intermittent basis. Slightly enriched uranium [less than 1% ^{235}U by weight and 0.68% of total mass (ORAUT 2010a, p. 23)] was also present at times in the form of scrap metal or residues.

Figure 6-6 shows estimated beta dose rates from a semi-infinite slab of uranium metal at various enrichment levels. For uranium enrichments up to 30%, the beta radiation field is dominated by contributions from ^{238}U decay products. Therefore, for depleted uranium, the most energetic contributor to the beta exposure is the 2.29-MeV (maximum energy) beta particle from ^{234m}Pa.

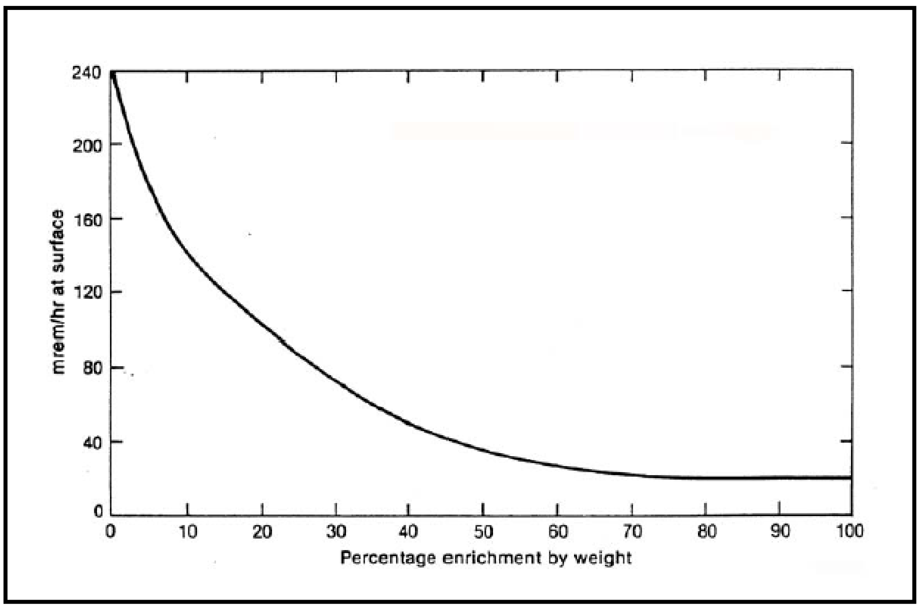

Figure 6-6. Estimated beta dose rate at surface of uranium metal at various enrichment levels (DOE 2009, p. 152).

Processes that separate and sometimes concentrate beta-emitting uranium progeny are not uncommon in DOE uranium facilities. Surface beta dose rates on the order of 1 to 20 rad/hr have been observed at some DOE facilities. Exposure control is complicated by the fact that considerable contact work takes place in facilities that process uranium metal. At MCW, and presumably WSP, chronic overexposure of workers' hands was a serious problem. Many operations required contact between the hands and the radioactive materials, and the glove program was "sketchy and inadequate" (Mason 1955).

The beta spectrum from uranium is highly dependent on the quantity of progeny in the uranium, which in turn is dependent on the enrichment level. Depleted uranium progeny grow into secular equilibrium relatively quickly (about 30 days); it is conservative to assume that progeny would have been present at these levels. Figure 6-7 shows the relative dose rate in relation to energy. Depleted uranium would be similar to the natural uranium used for this experiment.

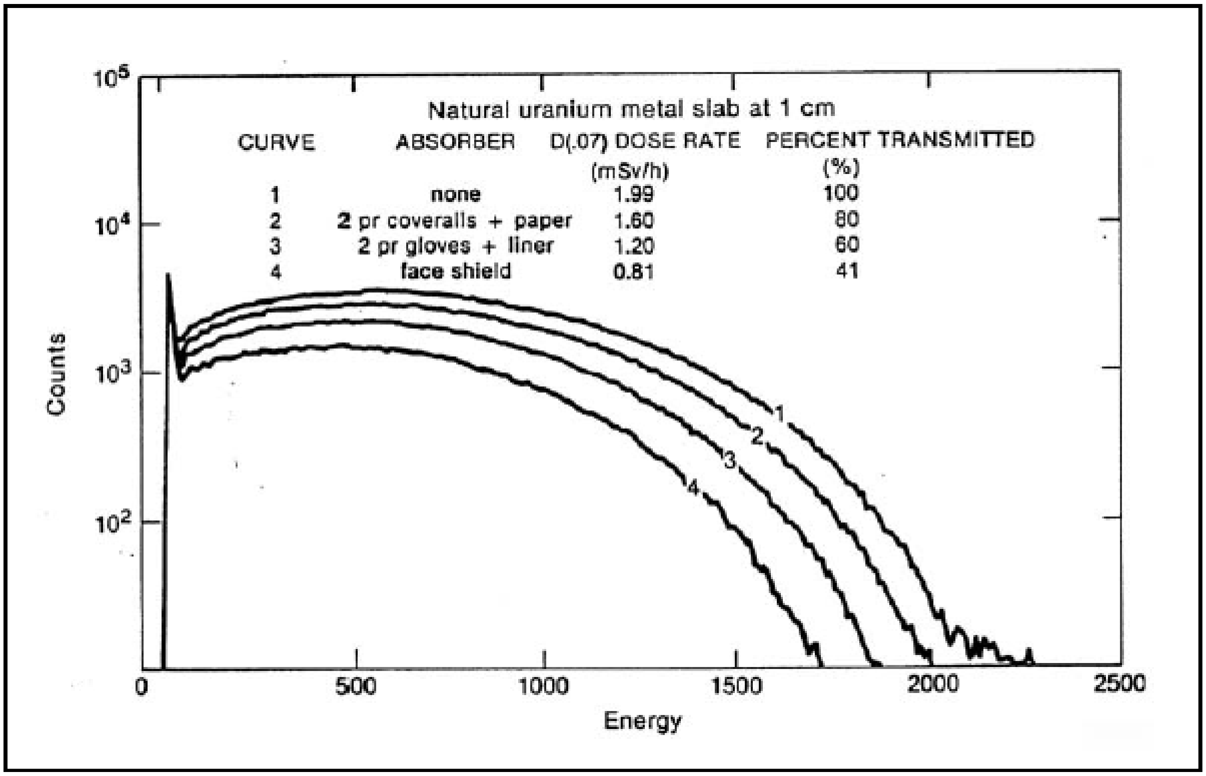

Figure 6-7. Shallow dose rate from natural uranium slab (DOE 2009, p. 154).

Although depleted uranium, slightly enriched uranium, and natural thorium were present in the waste stream processing buildings, the dose from these materials would be small in comparison with natural uranium because of the predominance of the latter (more than 97%) that was processed at the plant. Table 6-10 lists energy distributions for WSP buildings.

6.3.5 Reported-Dose-to-Organ-Dose Conversion Factor Units

The roentgen was the unit of calibration. It is reasonable to assume that this continued throughout the life of the WSP film dosimetry system. Little is known about the dosimetry system between plant shutdown and the remediation period. Calibration of the dosimetry system consistent with the DOE Laboratory Accreditation Program (DOELAP) was utilized during the remediation period. Thus, the personal dose equivalent [*Hp(10)*] is the appropriate unit to use for the remediation period. Tables 6-11 and 6-12 show these units.

Table 6-11. Photon dose units for use with organ dose conversion factors.

Year	Unit	Year	Unit	Year	Unit	Year	Unit	Year	Unit
1957	R	1967	R	1977		1987	$H_p(10)$	1997	$H_p(10)$
1958	R	1968	R	1978		1988	$H_p(10)$	1998	$H_p(10)$
1959	R	1969	R	1979		1989	$H_p(10)$	1999	$H_p(10)$
1960	R	1970		1980		1990	$H_p(10)$	2000	$H_p(10)$
1961	R	1971		1981		1991	$H_p(10)$	2001	$H_p(10)$
1962	R	1972		1982		1992	$H_p(10)$	2002	$H_p(10)$
1963	R	1973		1983		1993	$H_p(10)$		

1964	R	1974		1984		1994	$H_p(10)$		
1965	R	1975		1985	$H_p(10)$	1995	$H_p(10)$		
1966	R	1976		1986	$H_p(10)$	1996	$H_p(10)$		

Table 6-12. Electron dose units for use with organ dose conversion factors.

Year	Unit	Year	Unit	Year	Unit	Year	Unit	Year	Unit
1957	rad	1967	rad	1977		1987	*H'(0.07)*	1997	*H'(0.07)*
1958	rad	1968	rad	1978		1988	*H'(0.07)*	1998	*H'(0.07)*
1959	rad	1969	rad	1979		1989	*H'(0.07)*	1999	*H'(0.07)*
1960	rad	1970		1980		1990	*H'(0.07)*	2000	*H'(0.07)*
1961	rad	1971		1981		1991	*H'(0.07)*	2001	*H'(0.07)*
1962	rad	1972		1982		1992	*H'(0.07)*	2002	*H'(0.07)*
1963	rad	1973		1983		1993	*H'(0.07)*		
1964	rad	1974		1984		1994	*H'(0.07)*		
1965	rad	1975		1985	*H'(0.07)*	1995	*H'(0.07)*		
1966	rad	1976		1986	*H'(0.07)*	1996	*H'(0.07)*		

6.3.6 Limit of Detection

Miller (1955) describes an investigation of calibration data. The badge was very similar to that used throughout the early weapons program and it was likely the same or very similar as that used at Hanford (ORAUT 2010b, pp. 58) and the Savannah River Site (ORAUT 2005b, p. 91), which both state a minimum detectable level (MDL) of 0.040 mrem. A Hanford study of two-element dosimeters identified a detection level of about 40 mR at the upper 95% confidence level for radium gamma radiation (ORAUT 2010b, p. 41) and is repeated here:

> *Therefore, in the Hanford studies, dose results with these different dosimeter systems could be evaluated as described in Wilson et al. (1990). Wilson (1960b) described three changes in 1960 that led to a lower detection level of about 15 mrem at the 90% confidence level involving: (1) elimination of nonisotropic effect of calibration source, (2) automated film processing and (3) change to the more sensitive DuPont 508 film. He noted in this report a detection level of 40 mrem at the 95% confidence level for the Hanford two-chip dosimeter system with the DuPont 502 film used prior to these changes. An important consideration in this analysis concerned the level of potential missed dose. Wilson describes the analysis of 49 batches of Hanford routine calibration results that indicated a 25% standard deviation at the 30-mrem calibration level based on the optical density readings. Based on an analysis of the capabilities of the densitometer used to process the film, he estimated a likelihood of 0.33 (1/3) that a dose of 15 mrem would not be detected. The likelihood that this would occur for each successive monthly exchange for an entire year would be* $(0.33)^{12}$ *or about 1 in a million. Based on the 13 exchanges during the year at that time, he estimated a maximum potential missed dose of 195 mrem (i.e., 15 × 13). Conversely, Wilson estimated that about 8% of the time a positive dose would be recorded for dosimeters that received no exposure. A similar analysis could be performed for the dosimeter used prior to 1960 with an estimate that about 30 mrem would be detected one-third of the time.*

The MCW St. Louis Plant Site Profile (ORAUT 2009, p. 108) cites records in which gamma dose results are shown as "50*" where the asterisk refers to a footnote that reads, "indicates less than." Values of 60 and 80 with asterisks are sometimes found in the beta column. Based on this information, it is reasonable to adopt a more favorable-to-claimant MDL for the WSP film dosimeter of 50 mR gamma and 80 mrep beta. Landauer (the dosimeter manufacturer) typically quotes a minimum detection level of 10 mrem and does not report doses less than this level (DOE 1994). Tables 6-13 to 6-16 show these data.

Table 6-13. Photon MDLs for WSP dosimeters by year.

Year	MDL	Year	MDL	Year	MDL	Year	MDL	Year	MDL
1957	50 mR	1967		1977		1987		1997	10 mrem
1958	50 mR	1968		1978		1988		1998	10 mrem
1959	50 mR	1969		1979		1989		1999	10 mrem
1960	50 mR	1970		1980		1990		2000	10 mrem
1961	50 mR	1971		1981		1991			
1962	50 mR	1972		1982		1992			
1963	50 mR	1973		1983		1993			
1964	50 mR	1974		1984		1994	10 mrem		
1965	50 mR	1975		1985		1995	10 mrem		
1966	50 mR	1976		1986		1996	10 mrem		

Table 6-14. Potential missed photon dose.

Period of use	Dosimeter	MDL	Exchange frequency	Max. annual missed dose[a]
1957–1958	Two-element film	50 mR	Weekly (n = 52)	1,300 mR
			Biweekly (n = 24)	600 mR
1959–1969	Two-element film	50 mR	Monthly (n = 12)	300 mR
			Quarterly (n = 4)	100 mR
1975–1988			Monthly (n = 12)	
			Quarterly (n = 4)	
1989–2000	Landauer Alnor Type L-1	10 mR	Monthly (n = 12)	60 mrem
			Quarterly (n = 4)	20 mrem

a. Maximum annual missed dose calculated using (MDL × exchange frequency) ÷ 2, from OCAS-IG-001 (NIOSH 2007).

Table 6-15. Electron MDLs for WSP dosimeters by year.

Year	MDL	Year	MDL	Year	MDL	Year	MDL	Year	MDL
1957	80 mrep[a]	1967		1977		1987		1997	10 mrem
1958	80 mrep	1968		1978		1988		1998	10 mrem
1959	80 mrep	1969		1979		1989		1999	10 mrem
1960	80 mrep	1970		1980		1990		2000	10 mrem
1961	80 mrep	1971		1981		1991			
1962	80 mrep	1972		1982		1992			
1963	80 mrep	1973		1983		1993			
1964	80 mrep	1974		1984		1994	10 mrem		
1965	80 mrep	1975		1985		1995	10 mrem		
1966	80 mrep	1976		1986		1996	10 mrem		

a. 1 rep (Roentgen-equivalent-physical) is equal to about 83 ergs of energy absorbed per gram tissue. It is favorable to the claimant to assume that rep = rad = rem.

Table 6-16. Potential missed electron dose.

Period of use	Dosimeter	MDL	Exchange frequency	Max. annual missed dose[a]
1957–1966	Two-element film	80 mrep	Weekly (n=52)	2,080 mrep
			Semimonthly (n=24)	960 mrep
			Monthly (n=12)	480 mrep
1975–1988			Semimonthly (n=24)	
			Monthly (n=12)	
			Quarterly (n=4)	
1989–2000	Landauer Alnor Type L-1	10 mrem	Monthly (n=12)	60 mrem

a. Maximum annual missed dose calculated using (minimum detection limit × exchange frequency) ÷ 2, from OCAS-IG-001 (NIOSH 2007).

6.3.7 Exchange Frequency

Based on the historical evidence discussed in Section 6.1.3.1, it is favorable to claimants to assume that dosimeters were exchanged biweekly through 1958 and then monthly for operations workers and quarterly for all other workers during the WSP operational and initial cleanup periods. The one exception is that turret lathe and dingot operators had weekly exchanges through 1958.

6.3.7.1 Number of Zero Readings

If an individual's job assignment cannot be determined, the dose reconstructor should use the most frequent dosimeter exchange rate used during that year, which is favorable to the claimant. Table 6-17 lists tolerance limits in use at MCW, and presumably WSP, according to Mason (1955). The goal was to keep each individual's cumulative exposure to no greater than one-half the tolerance limit when aggregated over a 3-month period. Table 6-18 lists AEC standards for protection from external radiation that were in effect during the period of WSP operations (AEC 1963). Table 6-19 divides these Federal dose limits into the badge exchange period. Dose reconstructors should use dosimetry records, if available, to determine or estimate the exchange frequency. Using the methodology of NIOSH (2007), it is possible to develop a favorable-to-claimant estimate of the number of zeros and ultimately the missed dose.

Table 6-17. Tolerance limits at WSP.

Type of exposure	WSP tolerance limit per week
Beta to whole or partial body	500 mrep/wk
Gamma to whole or partial body	300 mR/wk
Beta & gamma to whole or partial body	500 mrep/wk
Hands and forearms	1,500 mrep/wk

Table 6-18. AEC standards.

Type of exposure	Period	Dose (rem)
Whole body, head and trunk, active blood-forming organs, gonads, or lens of eye	Accumulated dose	5 × (N – 18)
	Calendar quarter or 13 consecutive wks	3
Skin of whole body and thyroid	Year	30
	Calendar quarter or 13 consecutive wks	10
Hands and forearm, feet and ankles	Year	75
	Calendar quarter or 13 consecutive wks	25

Table 6-19. Dose limits based on exchange frequency.

Year	Limit	Exchange period: Biweekly	Exchange period: Monthly	Exchange period: Quarterly
1957–1958	500 mrep/wk	1 rep		
1959–1966	500 mrep/wk		2.167 rep	6.5 rep
1967–2000	5 rem/yr		0.417 rem	1.25 rem

6.3.7.2 Determination of Missed Dose

Determination of missed dose is performed using MDL/2 times the number of zero readings, as discussed in Section 2.1.2.2 of NIOSH (2007). If the number of zero readings is indeterminate, it can be estimated under the assumption that prorated dose limits were not exceeded.

6.3.8 Unmonitored Energy Range

The two-element film dosimeter used at WSP was similar to those used at other sites. The Savannah River Site TBD (ORAUT 2005b, pp. 92-95) discussed the response of this dosimeter. The dosimeter (shielded window) was calibrated with radium photons. The penetrating dose was evaluated by the response behind the cadmium metal filter. This heavy-metal filter attenuated the lower energy photons and should have resulted in an underestimated response behind that filter for measured dose and *Hp(10)*. Because most, but not all, penetrating radiations are above 30 keV, it is suggested that adjustments are necessary to satisfy dose reconstruction criteria of recorded penetrating whole-body doses due to the contribution to *Hp(10)* from low-energy photons, which include the L-X-rays from both uranium and thorium. It is estimated that a correction equal to 10% of the less-than-250 keV values be added to the *Hp(10)* dose due to the contribution of these low-energy photons to penetrating dose that would have been absorbed by the thick filter.

The DOELAP accreditation of the Landauer dosimeter system was based on a range of DOELAP exposure categories (DOE 1994). The response of the dosimeter was evaluated in relation to these exposures. Therefore, the Landauer dosimeter system is unlikely to have missed photon dose in an energy range to which workers could have been exposed. No correction for missed dose is appropriate for this dosimetry system.

6.3.9 Angular Dependence

The film dosimeter used at WSP had variant angular response. Dosimeters were not always exposed perpendicularly, which resulted in varying responses in relation to actual worker exposure. This dependence was considered as one factor when the response of the Hanford film badge was evaluated (ORAUT 2010b). This factor is included in the overall bias provided elsewhere in this TBD.

6.3.10 Uncertainty

6.3.10.1 Film

MCW used film to measure photons between 1957 and 1966. The film was DuPont dosimeter Type 552 film packets, which contained a DuPont Type 502 film and a DuPont Type 510 film. DuPont 502 film had a useful range from 10 or 20 mR up to approximately 10 R (NRC 1989).

A limited review of the calibration data developed from standard films developed with each batch was performed at MCW's St. Louis plant (Miller 1955). It is reasonable to assume that similar variability existed in the film badge processing at WSP. The Miller study provided an estimate of the laboratory random error associated with processing the film badges; it cited a ±50-mR maximum error at a 125-mR gamma calibration exposure. Therefore, a 40% error (95% upper bound) is assigned for the random uncertainty.

Hanford performed an evaluation of the two-element film dosimeter in a variety of exposure environments (ORAUT 2010b, p. 58). The factors included:

- Exposure geometry
- Energy response
- Mixed fields
- Missed dose
- Environmental effects

The exposure environment most appropriate to WSP is the fuel fabrication facility, in which workers were exposed to beta and gamma radiation from uranium. The identified bias factor [ratio of *Hp(10)* to recorded whole-body photon dose] ranges from 0.5 to 1.6. These are multiplicative factors [reported dose × bias factor = *Hp(10)*] and are appropriate to use for WSP doses. The midpoint of this bias range is close to 1, and it is therefore not appropriate to apply a bias based on these factors. The systematic uncertainty factor determined for the Hanford dosimeter (ORAUT 2010b, p. 58) is appropriate to use for the WSP dosimeter as well.

6.3.10.2 Thermoluminescent Dosimetry System

The Landauer TLD dosimetry system used during the remediation period was accredited by DOELAP. To meet accreditation requirements, the system passed performance testing consistent with DOE (1986). This standard allows a total error (precision + accuracy) of no more than 30%. Therefore, the worst would be a total bias of 30% or a total accuracy error of 30%.

6.3.11 <u>Geometric Correction Factor</u>

Consideration should be given to geometry when performing dose reconstruction for uranium facility workers who worked with uranium metals, powders, or residues or for workers who worked on equipment contaminated with uranium. An underestimation of the measured and missed photon doses could occur if the energy employee wore their dosimeter on the upper chest or lapel and not in the central area of the chest or on the waist. The organs located in the lower torso region are most affected. These include, but are not limited to, the stomach, liver, kidney, ureter, gall bladder, pancreas, small intestine, large intestine, rectum, ovaries, uterus, urinary bladder, and prostate.

The geometric correction factor calculated for application to the general population of workers is 2.1 and applied as a constant in IREP as determined in NIOSH (2010b). This geometric correction factor should be applied to the measured and missed photon doses for operators, material handlers, and trade workers including chemical operators, production operators, uranium material handlers, pipefitters, carpenters, welders, sheet metal workers, electricians, foremen, etc. Guidance in DCAS-TIB-0013, *Selected Geometric Exposure Scenario Considerations for External Dose Reconstruction at Uranium Facilities* (NIOSH 2010b), should be used to adjust the measured and missed photon dose to Weldon Spring workers. For glovebox workers, the geometric correction factor has a lognormal distribution with a geometric mean of 2.19 and a geometric standard deviation of 1.34 as stated in NIOSH (2011b).

6.4 ATTRIBUTIONS AND ANNOTATIONS

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

REFERENCES

AEC (U.S. Atomic Energy Commission), 1963, *Standards for Radiation Protection*, Appendix 0524, Washington, DC, August 12. [SRDB Ref ID: 1499]

Author unknown, circa 1958, *Film Badge Report 1958.* [SRDB Ref ID: 15871]

Author unknown, undated, “Personnel External Radiation Monitoring Program”, Mallinckrodt Chemical Works, Uranium Division, St. Louis, Missouri. [SRDB Ref ID: 15864, pp. 61-64]

Belcher, F. H., 1966a, “Report of Annual Health Protection Review at Mallinckrodt Chemical Works, Uranium, Division, Weldon Spring, 1965,” memorandum to H. M. Roth (Director, Research and Development Division, Oak Ridge Operations), with attached report dated October 1965, Atomic Energy Commission, St. Louis Area Office, Missouri, February 11. [SRDB Ref ID: 11806, pp. 5-10]

Belcher, F. H., 1966b, “Weldon Spring Health Protection Discussions,” memorandum to H. M. Roth (Director, Research and Development Division, Oak Ridge Operations), Atomic Energy Commission, St. Louis Area Office, Missouri, November 2. [SRBD Ref ID: 11806, pp. 2-4]

BMI (Battelle Memorial Institute), 2007, *Technical Information Bulletin: Default Assumptions and Methods for Atomic Weapons Employer Dose Reconstructions, Rev 00*, Battelle-TIB-5000/PNWD-3741, April 2. [SRDB Ref ID: 32016]

Brandner, K. E., 1956a, “Film Badge Procedures for Transfers to Weldon Spring and New Hires for Weldon Spring,” memorandum to M. G. Mason, Mallinckrodt Chemical Works, Uranium Division, St. Louis, Missouri, October 26. [SRDB Ref ID: 15578, pp. 3-4]

Brandner, K. E., 1956b, “Summary of the Mallinckrodt Chemical Works Film Badge Program,” memorandum to J. W. Miller, May, Mallinckrodt Chemical Works, Uranium Division, St. Louis, Missouri, May. [SRDB Ref ID: 15578, pp. 5-16]

Brandner, K. E., 1956c, “Conversion to the "rad" Unit,” memorandum to J. W. Miller, Mallinckrodt Chemical Works, Uranium Division, St. Louis, Missouri, June 16. [SRDB Ref ID: 15565]

Burr, R. H, 1959a, “Exchange of Turret Lathe Operators Film Badges,” memorandum to W. L. Utnage, Mallinckrodt Chemical Works, Uranium Division, St. Louis, Missouri, January 26. [SRDB Ref ID: 15864, p. 41]

Burr, R. H, 1959b, “Exchange of Film Badge Boards on January 30, 1959,” memorandum to W. L. Utnage, Mallinckrodt Chemical Works, Uranium Division, St. Louis, Missouri, January 29. [SRDB Ref ID: 15864, p. 42]

Burr, R.H.,1959c, *Weldon Spring Film Badge Program*, Mallinckrodt Chemical Works, Uranium Division, St. Louis, Missouri. [SRDB Ref ID: 15864, pp. 27-31]

DOE (U.S. Department of Energy), 1986, *Department of Energy Standard for the Performance Testing of Personnel Dosimetry Systems*, DOE/EH-0027, Office of Environment, Safety and Health, Washington, D.C., December. [SRDB Ref ID: 12294]

DOE (U.S. Department of Energy), 1994, *External Dosimetry Technical Basis Manual: Weldon Spring Site Remedial Action Project*, DOE/OR/21548-441, Rev. 0, Oak Ridge Operations Office, Oak Ridge, Tennessee, April. [SRDB Ref ID: 79446]

DOE (U.S. Department of Energy), 2000, *External Dosimetry Technical Basis Manual: Weldon Spring Site Remedial Action Project*, DOE/OR/21548-441, Rev. 6, Oak Ridge Operations Office, Oak Ridge Tennessee, January. [SRDB Ref ID: 32723]

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

Dupree-Ellis, E., J. Watkins, J. Ingle, and J. Phillips, 2000, "External Radiation Exposure and Mortality Among a Cohort of Uranium Processing Workers," *American Journal of Epidemiology*, volume 152, number 1, pp. 91-95. [SRDB Ref ID: 9486]

HEW (U.S. Department of Health, Education and Welfare), 1970, *Radiological Health Handbook (Revised Edition)*, Public Health Service, Food and Drug Administration, Bureau of Radiological Health, Rockville Maryland, January. [SRDB Ref ID: 75017, pp. 110, 112-113].

Ingle, N., 1998, "Mallinckrodt Chemical Works Dose Estimate Methodology," memorandum to B. Dupree (Oak Ridge Associated Universities), Delta-21 Resources, Inc., February 4. [SRDB Ref ID: 13176]

Mason, M. G., 1955, *Mallinckrodt Chemical Works Health Program: Policies, Status and Summary*, Mallinckrodt Chemical Works, St. Louis, Missouri, February 21. [SRDB Ref ID: 13180]

MCW (Mallinckrodt Chemical Works), 1956, *Film Badge, Technique and Calibration*, Uranium Division, St. Louis, Missouri, November 1. [SRDB Ref ID: 15864, pp. 2-10]

MCW (Mallinckrodt Chemical Works), 1958, "Weldon Spring Plant Film Badge Program," memorandum to W. L. Utnage, Uranium Division, Health and Safety Department, Weldon Spring, Missouri. [SRDB Ref ID: 15864, p. 32]

MCW (Mallinckrodt Chemical Works), 1965, *Summary of Health Protection Practices (Revised 1965)*, Uranium Division, St. Louis, Missouri. [SRDB Ref ID: 14998]

MCW (Mallinckrodt Chemical Works), date unknown, *Personnel External Radiation Monitoring Program*, Uranium Division, St. Louis, Missouri. [SRDB Ref ID: 15864, pp. 61-64]

Miller, J. W., 1955, "Investigation of Film Badge Standards Calibration Data," memorandum to M. G. Mason, Mallinckrodt Chemical Works, St. Louis, Missouri, February 3. [SRDB Ref ID: 6513, pp. 58-64]

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. [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. [SRDB Ref ID: 88929]

NIOSH (National Institute for Occupational Safety and Health), 2010b, *Technical Information Bulletin: Selected Geometric Exposure Scenario Considerations for External Dose Reconstruction at Uranium Facilities, Rev 1*, Division of Compensation Analysis and Support, DCAS-TIB-0013, November 23. [SRDB Ref ID: 90694]

NIOSH (National Institute for Occupational Safety and Health), 2011a, Advisory Board on Radiation and Worker Health Work Group on Weldon Spring meeting. September 13. [SRDB Ref ID: 120526 pp. 136-139]

NIOSH (National Institute for Occupational Safety and Health), 2011b, *Technical Information Bulletin: Best Estimate External Dose Reconstruction for Glovebox Workers, Rev 4*, Division of Compensation Analysis and Support, DCAS-TIB-0010, November 28. [SRDB Ref ID: 104815]

NRC (National Research Council), 1989, *Film Badge Dosimetry in Atmospheric Nuclear Tests*, National Academy Press, Washington D.C. [SRDB Ref ID: 1905]

ORAUT (Oak Ridge Associated Universities Team), 2004, *Technical Basis Document for the Fernald Environmental Managemnt Project – Occupational External Dose*, ORAUT-TKBS-0017-6, Rev. 00, Oak Ridge, Tennessee, April 20.

ORAUT (Oak Ridge Associated Universities Team), 2005a, *Technical Basis Document for the Weldon Spring Plant – Site Description*, ORAUT-TKBS-0028-2, Revision 00, Oak Ridge, Tennessee, June 24.

ORAUT (Oak Ridge Associated Universities Team), 2005b, *Savannah River Site*, ORAUT-TKBS-0003, Rev. 03, Oak Ridge, Tennessee, April 5.

ORAUT (Oak Ridge Associated Universities Team), 2010, *Basis for Development of an Exposure Matrix for the Mallinckrodt Chemical Company St. Louis Downtown Site and the St. Louis Airport Site, St. Louis, Missouri,* ORAUT-TKBS-0005, Rev. 03, Oak Ridge, Tennessee, November 22.

ORAUT (Oak Ridge Associated Universities Team), 2010a, *SEC Petition Evaluation Report for the Weldon Spring Plant*, Petition SEC-00143, Rev 00, Oak Ridge, Tennessee, April 16.

ORAUT (Oak Ridge Associated Universities Team), 2010b, *Hanford Site – Occupational External Dosimetry*, ORAUT-TKBS-0006-6, Rev. 04, Oak Ridge, Tennessee, January 7.

Parker, H. M., 1980, “Health Physics, Instrumentation and Radiation Protection, Hanford Engineer Works,” *Health Physics*, volume 38, pp. 957–996.

Shleien, B., L. A. Slaback, Jr., and B. K. Birky, 1998, *Handbook of Health Physics and Radiological Health*, 3rd Edition, Lippincott, Williams and Wilkins, Philadelphia, Pennsylvania. [SRDB Ref ID: 22737]

Watson, J. E., J. L. Wood, W. G. Tankersley, and C. M. West, 1994, "Estimation of Radiation Doses for Workers without Monitoring Data for Retrospective Epidemiologic Studies," *Health Physics*, volume 67, number 4, pp. 402–405. [SRDB Ref ID: 8601]

GLOSSARY

beta dose
Designation (i.e., beta) on some records for external dose from beta and less-energetic X-ray and gamma radiation, often for shallow dose or dose to the lens of the eye.

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.

bremsstrahlung
Electromagnetic radiation released as a result of inelastic scattering of a moving charged particle within the nucleus of an atom. X-rays produced in a typical medical X-ray tube frequently originate from inelastic scattering of accelerated electrons in the anode material.

deep absorbed dose
Absorbed dose in units of rem or sievert at a depth of 1 centimeter (1,000 milligrams per square centimeter). See *dose*.

deep dose equivalent [$H_p(10)$]
Dose equivalent in units of rem or sievert for a 1-centimeter depth in tissue (1,000 milligrams per square centimeter). See *dose*.

depleted uranium
Uranium with a percentage of ^{235}U lower than the 0.7% found in natural uranium.

DOE Laboratory Accreditation Program (DOELAP)
Program for accreditation by DOE of DOE site personnel dosimetry and radiobioassay programs based on performance testing and the evaluation of associated quality assurance, records, and calibration programs.

dose
In general, the specific amount of energy from ionizing radiation that is absorbed per unit of mass. Effective and equivalent doses are in units of rem or sievert; other types of dose are in units of roentgens, rads, reps, or grays.

dose equivalent (*H*)
In units of rem or sievert, product of absorbed dose in tissue multiplied by a weighting factor and sometimes by other modifying factors to account for the potential for a biological effect from the absorbed dose. See *dose*.

dosimeter
Device that measures the quantity of received radiation, usually a holder with radiation-absorbing filters and radiation-sensitive inserts packaged to provide a record of absorbed dose received by an individual. See *film dosimeter* and *thermoluminescent dosimeter*.

dosimetry
Measurement and calculation of internal and external radiation doses.

dosimetry system
System for assessment of received radiation dose. This includes the fabrication, assignment, and processing of external dosimeters, and/or the collection and analysis of bioassay samples, and the interpretation and documentation of the results.

electron
Basic atomic particle with negative charge and a mass 1/1,837 that of a proton. Electrons surround the positively charged nucleus of the atom.

exchange period
Period (weekly, biweekly, monthly, etc.) for routine exchange of dosimeters. Also called exchange frequency.

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.

extremity
The portion of the arm from and including the elbow through the fingertips and the portion of the leg from and including the knee and patella through the toes.

field calibration
Dosimeter calibration based on radiation types, intensities, and energies in the work environment.

film
In the context of external dosimetry, radiation-sensitive photographic film in a light-tight wrapping. See *film dosimeter*.

film density
See *optical density*.

film dosimeter
Package of film for measurement of ionizing radiation exposure for personnel monitoring purposes. A film dosimeter can contain two or three films of different sensitivities, and it can contain one or more filters that shield parts of the film from certain types of radiation. When developed, the film has an image caused by radiation measurable with an optical densitometer. Also called film badge.

fission
Splitting of the nucleus of an atom (usually of a heavy element) into at least two other nuclei and the release of a relatively large amount of energy. This transformation usually releases two or three neutrons.

fissionable
Capable of undergoing fission by capturing neutrons, including fast neutrons. Uranium-238 is fissionable. Fissionable indicates both spontaneous and induced fission.

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.

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 *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.

neutron
Basic nucleic particle that is electrically neutral with mass slightly greater than that of a proton. There are neutrons in the nuclei of every atom heavier than normal hydrogen. 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. See *neutron*.

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.

open window
Area of a film dosimeter that has little to no radiation shielding (e.g., only a holder and visible light protection). See *film dosimeter*.

operating area
Usually refers to a major operational work area at a site.

optical density
Measure of the degree of opacity of photographic or radiographic film defined as $OD = \log_{10} (I_0/I)$, the base-10 logarithm of the ratio of the reference light intensity I_0 (without film) to the transmitted light intensity (through the film). Also called film density and density reading.

personal dose equivalent *Hp(d)*
Dose equivalent in units of rem or sievert in soft tissue below a specified point on the body at an appropriate depth *d*. The depths selected for personal dosimetry are 0.07 millimeters (7 milligrams per square centimeter) and 10 millimeters (1,000 milligrams per square centimeter), respectively, for the skin (shallow) and whole-body (deep) doses. These are noted as $H_p(0.07)$ and $H_p(10)$, respectively. The International Commission on Radiological Measurement and Units recommended $H_p(d)$ in 1993 as dose quantity for radiological protection.

photon
Quantum of electromagnetic energy generally regarded as a discrete particle having zero rest mass, no electric charge, and an indefinitely long lifetime. The entire range of electromagnetic radiation that extends in frequency from 10^{23} cycles per second (hertz) to 0 hertz.

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

quality factor, *Q*
Principal modifying factor (which depends on the collision stopping power for charged particles) that is employed to derive dose equivalent from absorbed dose. The quality factor multiplied by the absorbed dose yields the dose equivalent. See *dose*.

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

radioactive
Of, caused by, or exhibiting radioactivity.

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

radionuclide
Radioactive nuclide. See *radioactive* and *nuclide*.

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.

rep
Historical quantity of radiation (usually other than X-ray or gamma radiation) originally defined as 83 ergs absorbed per gram in the body and redefined in the 1940s or early 1950s as the amount that would liberate the same amount of energy (93 ergs per gram) as 1 roentgen of X- or gamma rays. Replaced by the gray in the International System of Units; 1 rep is approximately equal to 8.38 milligray. The word derives from roentgen equivalent physical.

roentgen
Unit of photon (gamma or X-ray) exposure for which the resultant ionization liberates a positive or negative charge equal to 2.58×10^{-4} coulombs per kilogram (or 1 electrostatic unit of electricity per cubic centimeter) of dry air at 0°C and standard atmospheric pressure. An exposure of 1 R is approximately equivalent to an absorbed dose of 1 rad in soft tissue for higher energy photons (generally greater than 100 kiloelectron-volts).

shallow absorbed dose (*Ds*)
Absorbed dose at a depth of 0.07 millimeters (7 milligrams per square centimeter) in a material of specified geometry and composition.

shallow dose equivalent (*Hs*)
Dose equivalent in units of rem or sievert at a depth of 0.07 millimeters (7 milligrams per square centimeter) in tissue equal to the sum of the penetrating and nonpenetrating doses.

shielding
Material or obstruction that absorbs ionizing radiation and tends to protect personnel or materials from its effects.

sievert (Sv)
International System unit for dose equivalent, which indicates the biological damage caused by radiation. The unit is the radiation value in gray (equal to 1 joule per kilogram) multiplied by a weighting factor for the type of radiation and a weighting factor for the tissue; 1 Sv equals 100 rem.

skin dose
See *shallow dose equivalent*.

thermoluminescent dosimeter (TLD)
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.

U.S. Atomic Energy Commission (AEC)
Federal agency created in 1946 to assume the responsibilities of the Manhattan Engineer District (nuclear weapons) and to manage the development, use, and control of nuclear energy for military and civilian applications. The U.S. Energy Research and Development Administration and the U.S. Nuclear Regulatory Commission assumed separate duties from the AEC in 1974. The U.S. Department of Energy succeeded the U.S. Energy Research and Development Administration in 1979.

whole-body dose
Dose to the entire body excluding the contents of the gastrointestinal tract, urinary bladder, and gall bladder and commonly defined as the absorbed dose at a tissue depth of 10 millimeters (1,000 milligrams per square centimeter). Also called penetrating dose. See *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.

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LIST OF FIGURES

FIGURE **PAGE**

FORM 7229

MALLINCKRODT CHEMICAL WORKS

ANNUAL PERSONNEL INTERNAL - EXTERNAL RADIATION EXPOSURE REPORT HEALTH & SAFETY DEPT.

URANIUM DIVISION

[redacted] CLOCK NO. EMPLOYEE NAME 370 DEPT. WKS. EMPLOYED

EXTERNAL RADIATION FILM BADGE	GAMMA mrem	BETA mrem	GAMMA + BETA mrem
CUMULATIVE THRU 1958	115	238	353
1 FOR QUARTER 1959		71	71
2 " " 1959	75	139	214
3 " " 1959		99	99
4 " " 1959	38	72	110
TOTAL FOR 1959	113	381	494
CUMULATIVE EXPOSURE FOR 1959	228	619	847
WEEKLY AVERAGE FOR 19	2	7	10

INTERNAL RADIATION EXPOSURE	URINARY URANIUM AVG. CONCENTRATION μg/l MON.	FRI.	AVG. DUST CONCENTRATION dpm/m³
1953			
1954			
1955			
1956			
1957			
1958	10		
3 QUARTER 1959	5		
4 " 1959		3	
" 19			
" 19			
AVG. FOR YEAR 1959	6	3	

Figure A-1. Example of Annual Personnel Internal-External Exposure Report.

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PERSONNEL INTERNAL-EXTERNAL RADIATION
SUMMARY 1963-64

CLOCK NO. [redacted] NAME [redacted] [redacted]

EXTERNAL RADIATION	GAMMA		GAMMA/BETA	
FOR QUARTER 1 1963	00083		00314	
2 1963	00082		00210	
3 1963	00124		00233	
4 1963	00021		00310	
TOTAL 1963	00310	00757	01067	—
1 1964	00022		00167	
2 1964	00023		00231	
3 1964	00029		00100	
4 1964	00091		00234	
TOTAL 1964	00165	00567	00732	—

Figure A-2. Example of Personnel Internal-External Radiation Summary.

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ANNUAL PERSONNEL INTERNAL-EXTERNAL
RADIATION EXPOSURE REPORT
HEALTH & SAFETY DEPT.

CLOCK NO.	EMPLOYEE NAME	DEP.	WKS.	DATE EMP.
[redacted]	[redacted]	370	- - -	- - -

EXTERNAL RADIATION FILM BADGE		GAMMA MREM	BETA MREM	GAMMA/BETA MREM
CUMULATIVE THRU	1960	364	2449	2813
FOR QUARTER 1	1961	19	212	231
2	1961	36	324	360
3	1961	17	203	220
4	1961	25	395	420
TOTAL FOR	1961	97	1134	1231
CUMULATIVE THRU	1961	461	3583	4044
WEEKLY AVER.	1961	2	23	25

INTERNAL RADIATION EXPOSURE		URINARY URANIUM AVER. CONCENTRATION UG/L	
		MON.	FRI.
	1954		
	1955		
	1956		
	1957		
	1958	10	
	1959	6	3
	1960	9	6
FOR QUARTER 1	1961	6	13
2	1961		
3	1961	20	35
4	1961		
AVER. FOR YR.	1961	11	24

Figure A-3. Example of Annual Personnel Internal-External Radiation Exposure Report.

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JANUARY 15 1964

ANNUAL
PERSONNEL EXTERNAL RADIATION
EXPOSURE REPORT
YEAR 1963

GROUP-UNIT 0308 [redacted] [redacted] CLOCK NO. [redacted]

UNITS ARE GAMMA -MILLIROENTGEN, BETA & GAMMA -MILLIREP

YEARLY TOTAL BETA & GAMMA	1067
YEARLY TOTAL GAMMA	310
PERCENT OF YEARLY MPC BETA & GAMMA	3
PERCENT OF YEARLY MPC GAMMA	6
LIFETIME CUMULATIVE TOTAL BETA & GAMMA	6937
LIFETIME CUMULATIVE TOTAL GAMMA	942
PERCENT OF CUMULATIVE MPC BETA & GAMMA	4
PERCENT OF CUMULATIVE MPC GAMMA	0
YEARLY AVERAGE LAST 5 YEARS BETA & GAMMA	1316
YEARLY AVERAGE LAST 5 YEARS GAMMA	165

Figure A-4. Example of Annual Personnel External Radiation Exposure Report.

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[redacted]

NAME	SOC SEC NO	DATE OF BIRTH
[redacted]	[redacted]	[redacted]

MALLINCKRODT EMPLOY DATE [redacted]

RECORDED EXTERNAL EXPOSURE

YEAR	GAMMA	BETA&GAMMA	
1962	.171	1.826	
1963	.310	1.067	
1964	.165	.732	
1965	.287	1.404	
1966	.144	.235	
LIFETIME	1.538	9.308	AEC GUIDE 90

RECORDED INTERNAL EXPOSURE

YEAR	QTR	MON	FRI	MON
1963	1ST	0012	0028	
	2ND			
	3RD	0012	0005	0004
	4TH	0009	0010	
1964	1ST	0025	0021	
	2ND	0007	0014	
	3RD	0006	0015	
	4TH	0005	0026	
1965	1ST	0015	0007	
	2ND	0003	0022	
	3RD	0012	0007	
	4TH			
1966	1ST	0014	0004	
	2ND	0006		
	3RD			
	4TH			

Recorded External Exposure 1966

Month	mγ	β+γ
may	.011	.039
JUNE	.035	.065
July	.010	.040
Aug	000	000
Sept	.020	.045
oct	.045	.190
1966 Total	.265	.614

Figure A-5. Example employee recorded external and internal exposure record.

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JANUARY 22 1964

QUARTERLY
EXTERNAL RADIATION
EXPOSURE REPORT
JUNE
1963

GROUP NO	NAME	MONTH	BETA&G	GAMMA	YEAR TO DATE BETA&G	YEAR TO DATE GAMMA	CLOCK NO
	[redacted]	04	33	33			[redacted]
		05	17	0			
		06	33	29			
		QTR	83	62	250	95	
	[redacted]	04	317	316			[redacted]
		05	317	209			
		06	367	366			
		QTR	1001	891	1797	1681	
	[redacted]	04	114	22			[redacted]
		05	25	21			
		06	71	39			
		QTR	210	82	524	165	
	[redacted]	04					[redacted]
		05					
		06					
		QTR	0	0	0	0	
	[redacted]	04	94	44			[redacted]
		05	84	0			
		06	53	42			
		QTR	231	86	429	120	
	[redacted]	04	556	87			[redacted]
		05	195	42			
		06	272	84			
		QTR	1023	213	1959	512	
	[redacted]	04					[redacted]
		05					
		06	138	71			
		QTR	138	71	588	98	
	[redacted]	04	299	76			[redacted]
		05					
		06	121	39			
		QTR	420	115	1077	209	
	[redacted]	04	44	44			[redacted]
		05	25	10			
		06	27	21			
		QTR	96	75	480	144	

Figure A-6. Example of Quarterly External Radiation Exposure Report.

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FILM BADGE DATA SUMMARY

NAME [redacted] S.S. No. [redacted] File Nos. [redacted]

DATES: Birth [redacted]; U.D. Med. Exam. - First ______ Last ______

YEARS IN MCW U.D. ______. First Film Badge Record Year 1943 ______ (1)

TERMINATED FROM ☐ Destrehan, ☐ W.S. To Parent Co. ☐, Approx. Date ______

	RECORDED FILM BADGE RESULTS			
PERIOD	GAMMA RAD	BETA REP	G + B RAD	COMMENTS
Cum. thru 12/52	13.25	20.38	33.63	
(2) CY 1953	.39	.47	.86	
1954	.67	.05	.72	
1955	.38	.30	.68	
1956	.31	.27	.58	
1957	.18	.27	.45	
(3) 1958	.05	.00	.05	
1959	.09	.26	.35	
1960	.07	.17	.24	
1961	.06	.38	.44	
1962	.11	1.01	1.12	
1963	.18	.08	.26	
1964	.38	.14	.52	
1965	.50	.65	1.15	
1966	.23	.09	.32	
TOTALS	16.85	24.52	41.37	

For ______ years

Average per year ______ ______ ______

LIFETIME DOSE STATUS

On ______, N-18 = ______ yrs. X 5 = ______ Rad. Gamma for AEC Guide

Percent of Guide = ______ Total Gamma ÷ ______ Guide Gamma X 100 = ______ %

(1) Prior to 5/31/48, film badge program by University of Rochester.
(2) For period prior to 1/53, data are summarized on single file card. Subsequent period summarized annually on individual card, or, on IBM printouts.
(3) During start-up at Weldon Spring in 1958 and later, some persons were not badged because not involved in radiation work.

NAME [redacted] File Nos. [redacted] AEC ______

Figure A-7. Example of Film Badge Data Summary by year.