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ACRONYMS AND ABBREVIATIONS

AEC	U.S. Atomic Energy Commission
cm	centimeter
DOE	U.S. Department of Energy
DOELAP	DOE Laboratory Accreditation Program
EEOICPA	Energy Employees Occupational Illness Compensation Program Act
g	gram
keV	kilovolt-electron, 1,000 electron volts
LOD	limit of detection
MCW	Mallinckrodt Chemical Works
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 Ride Associated Universities
R	roentgen
TBD	Technical Basis Document
TLD	thermoluminescent dosimeter
U.S.C.	United States Code
wk	week
WSP	Weldon Spring Plant
yr	year
α	alpha
β	beta
γ	gamma

6.1 INTRODUCTION

This Technical Basis Document (TBD) provides information about documentation of historical practices at the Weldon Spring Plant (WSP) for evaluation of external exposure data for monitored and unmonitored workers to be used as a supplement to or substitute for recorded individual worker dose.

TBDs and Site Profile Documents are general working documents that provide guidance concerning 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 the National Institute for Occupational Safety and Health (NIOSH) 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 facility" as defined in the Energy Employees Occupational Illness Compensation Program Act of 2000 [EEOICPA; 42 U.S.C. Sections 7384l(5) and (12)].

6.1.1 Purpose

The purpose of this document is to describe WSP external dosimetry systems and practices.

6.1.2 Scope

WSP operations played an important role in the U.S. development of nuclear power and nuclear weapons. Operations focused on 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 2002) 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, this document 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.

6.1.3 Dosimetry Overview

With few exceptions, the WSP processed uranium, but a small amount of thorium was processed near the end of the plant's operations. *Technical Basis Document for the Weldon Spring Plant – Site Description* (ORAU 2005) 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. Pa-234m also 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).

Radiation protection practices and exposures at WSP varied over time. There is no comprehensive description of the practices and processes available at this time. 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.

6.1.3.1 Plant Operations Period (1957 to 1966)

A film badge notification memorandum by the Health and Safety Department (MCW 1958) indicates that the WSP film badge program began on March 1, 1958. Before that time, dosimetry performed 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 fig. 6A-7.)

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. However, Burr (1959b) states that "monthly exchange of film badges for all plant personnel is scheduled for January 30, 1959." An undated report entitled "Personnel External Radiation Monitoring Program" (MCW undated) describes the MCW program. It states that "wage personnel film badges are exchanged monthly and salaried personnel film badges quarterly." A 1965 Summary of Health Protection Practices states that "operations badges are exchanged and processed on a calendar month schedule, all others on a three-month schedule." If the exchange frequency cannot be explicitly identified, the dose reconstructor should make the claimant-favorable assumption to use the most frequent exchange frequency for the period.

Actinium Series (4n + 3)*

Nuclide	Historical name	Half-life	Major radiation energies (MeV) and intensities†		
			α	β	γ
$^{235}_{92}U$	Actinouranium	7.1 ×10⁸y	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	3.25×10⁴y	4.95 (22%) 5.01 (24%) 5.02 (23%)	---	0.027 (6%) 0.29c (6%)
$^{227}_{89}Ac$ (98.6% → $^{227}_{90}Th$; 1.4% → $^{223}_{87}Fr$)	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% → $^{211}_{82}Pb$; .00023% → $^{215}_{85}At$)	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% → $^{211}_{84}Po$; 99.7% → $^{207}_{81}Tl$)	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. (taken from HEW 1970)

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%)
$^{234}_{91}Pa^m$	Uranium X_2	1.17m	---	2.29 (98%)	0.765 (0.30%) 1.001 (0.60%)
99.87% / 0.13%					
$^{234}_{91}Pa$	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%)
$^{218}_{84}Po$	Radium A	3.05m	6.00 (~100%)	0.33 (~0.019%)	---
99.98% / 0.02%					
$^{214}_{82}Pb$	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%)	---
$^{214}_{83}Bi$	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%)
99.98% / 0.02%					
$^{214}_{84}Po$	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%)
$^{210}_{83}Bi$	Radium E	5.01d	4.65 (.00007%) 4.69 (.00005%)	1.161 (~100%)	---
~100% / .00013%					
$^{210}_{84}Po$	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. (taken from 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% → $^{212}_{84}Po$; 36.0% → $^{208}_{81}Tl$	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., Table of Isotopes (6th ed.; New York: John Wiley & Sons, Inc., 1967) and Hogan, O. H., Zigman, P. E., and Mackin, J. L., Beta Spectra (USNRDL-TR-802 [Washington, D.C.: U.S. Atomic Energy Commission, 1964]).

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

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 of the badge 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 onto the back of the badge. The film was DuPont dosimeter type 552 film packets, which contained two dental-size films wrapped together in a single wrapper. One of the films was apparently a DuPont type 502 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 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. These badges were changed once every 2 wk.

A 1965 document 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* (MCW 1965).

Personnel in operating areas of the plant and in some laboratories were required to wear badges continuously at work. Permanent badges were also assigned to those worker 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. Fixed location badges were installed in process areas to provide reference data about changes in average radiation level. Use of film badges by visitors or subcontract personnel was predetermined by the person who authorized entry (MCW 1965).

MCW (1965) also stated that "operations badges are exchanged and processed on a calender [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." Dupree et al. (1999) stated that film badges were read weekly from 1945 to 1954 (which would be pre-Weldon Spring), biweekly from 1955 to 1958 (which includes the initial startup of Weldon Spring), and monthly for production workers and quarterly for all other workers from 1959 to 1966. In light of this confusion, it is suggested that if the exchange frequency cannot be determined from the claimant file, a client-favorable exchange frequency of bi-weekly be assumed for all operations workers through 1958 and that an exchange frequency of monthly for production workers and quarterly for all other workers be assumed from 1959 to 1969.

Belcher (1966a) described monitoring for external radiation exposure as using a "stainless steel non-security badge containing a DuPont 555 film." This badge supposedly 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.

6.1.3.2 Initial Cleanup Period (1967 to 1969)

No information is currently available to describe the external dosimetry program during the initial cleanup 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 that case, it is likely that the same film badge system would have been used.

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 staff.

6.1.3.3 Monitoring and Maintenance Period (1969 to 1985)

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

6.1.3.4 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).

6.2 DOSE RECONSTRUCTION PARAMETERS

6.2.1 Interpreting the External Dosimetry Record

Table 6-2 lists the process used to evaluate the measured film densities and to determine dose. Table 6-3 cites the one identified bias correction to be applied to WSP recorded dose values.

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 1958–1966	$SW_{density}$ $OW_{density}$ $OW_{density,beta} = OW_{density} - (G_{dose} \div CF_{OW,gamma})$	$G_{dose} = SW_{density} \times CF_{SW,gamma}$ $B_{dose} = OW_{density,beta} \times CF_{OW,beta}$
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).

Table 6-3. Adjustments to recorded dose.

Period	Dosimeter	Facility	Adjustment to reported dose
1957–1966	Two-element film	WSP	Estimate neutron dose as 10% of reported gamma dose in facilities containing UF_4 or UF_6.

6.2.2 Weldon Spring 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).

6.2.2.1 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 in units of mR (or 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). In this TBD, a rep is defined as an absorbed dose of 93 ergs/g. It does not appear that the conversion to rad was accomplished. It is assumed that the 93-ergs/g rep was used throughout the WSP production years.

It is claimant-favorable to assume that roentgens (R or r in the records), rep, and rem are equivalent.

6.2.2.2 Discrepancies

If the employee's record contains discrepancies, it is claimant-favorable 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 claimant-favorable to use that dose in the dose reconstruction. The dose reconstructor should use best judgment to credit the dose to the most likely year.

6.2.2.3 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 claimant-favorable assumption is that the dosimeter was lost, and dose should be assigned for that period using the dosimetry data from before and after that period (consider the approach of Watson et al. 1994).

6.2.2.4 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. Table 6-4 summarizes assignment of film badges. Table 6-5 lists badged areas and nonbadged areas.

Table 6-4. Assignment of film badges.

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 of otherwise) who do not normally work in badge areas but find it necessary to enter a badge area for a limited time.

Table 6-5. Badged and nonbadged areas.

Badge area	Nonbadged 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 workers. Wage personnel film badges were exchanged and processed monthly, and salaried personnel film badges were exchanged and processed quarterly. Individual film badge data were posted quarterly to the employee's health history file.

6.2.2.5 Interpretation of Reported Data

Table 6-6 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 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 claimant-favorable to assume that all units are rem. Fig. 6A-7 shows a film badge summary report that includes data from multiple years.

Table 6-6. Interpretation of reported data.

Report	Reported quantity	Interpretation of zeroes	Interpretation of blanks (no data)	Individual and annual data	Monitored/ unmonitored
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 likely indicates a monitored exposure reported as zero.	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, beta, and gamma + beta (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, W. S., and had notes for worker transfer to parent company with date noted.	Zero likely indicates a monitored exposure reported as zero.	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, gamma (mrem), beta (mrem), and gamma + beta (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 likely indicates a monitored exposure reported as zero.	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 gamma and « gamma/beta. » No indication of units. Gamma/beta represents total external exposure for the period.	Zero likely indicates a monitored exposure reported as zero.	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, gamma (mrem), beta (mrem), and total, noted as « gamma/beta » (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 print out. The weekly average external is also reported. Internal radiation exposure is reported on same form.	Zero likely indicates a monitored exposure reported as zero.	Blank indicates unmonitored during that period.		
Annual Personal External Radiation Exposure Report Year 19xx. (Figure A-4) Computer-generated report.		Zero likely indicates a monitored exposure reported as zero.	Blank indicates unmonitored during that period.		

Table 6-6 (Continued). Interpretation of reported data.

Report	Reported quantity	Interpretation of zeroes	Interpretation of blanks (no data)	Individual and annual data	Monitored/ unmonitored
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 beta and gamma by year. Lifetime values for each. No indications of units, but presumably are mrem.	Zero likely indicates a monitored exposure reported as zero.	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 beta & gamma and gamma alone. Units not specified, but presumed to be mrem. Month identified numerically. Year-to-date beta & gamma and gamma values also given for each employee.	Zero likely indicates a monitored exposure reported as zero.	Blank indicates unmonitored during that period.		

6.2.3 <u>Plant-Wide Dosimetry Results</u>

Available worker data was 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 6-7, there were over 70 different job titles for workers. These are categorized into nine categories that roughly represent the reported job titles. Table 6-8 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 each year. Exposure to beta radiation was substantially greater for those in the operator category than for any other job category.

6.2.3.1 Calibration

The film badges used by MCW at the St. Louis site were calibrated using known exposures given to control films (Miller 1955). The same system was used by MCW 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 curve, results are expressed in mr of gamma (radium equivalent) and mrep of beta (uranium equivalent). A direct conversion to mrad is assumed in recording personnel exposure.*

6.2.4 <u>Workplace Radiation Fields</u>

No data is readily available to describe the workplace radiation fields at WSP. Summary reports indicate that natural uranium was the material that the workers came into contact with most frequently. Radiation fields most often consisted of a complex mixture of beta and gamma energies. Neutrons were potentially encountered in several buildings as described in Section 6.2.4.2. 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 in relatively close proximity to the source, but which do not penetrate deeply into the body.

Table 6-7. 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
Nonradiation job	Computer Operator
	Industrial Nurse
	Inventory Control Clerk
	Maintenance and Utility Control Clerk
	Office Boy/Accounting Clerk
	Shipping
Safety, security	Production/Safety and Fire Marshall
	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
Operator	Acid Recovery/Loader
	Chemical D95 Operator
	Chemical Operator, store keeper
	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
	Chemical and Project Engineer
Engineer	Chemical Engineer
	Engineer and Production Control
	Mechanical Engineer
	Plant Engineer
	Process Engineer
	Analytical Chemist
Laboratory worker	Chemical Technician
	Laboratory Technician
	Laboratory Technician, Engineer
	Research Chemist

6.2.4.1 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, slightly enriched, or 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 that 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 2001). 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

Table 6-8. Annual average gamma and beta dose (mR).

	Annual average gamma exposure by year									
Job description	**1957**	**1958**	**1959**	**1960**	**1961**	**1962**	**1963**	**1964**	**1965**	**1966**
Engineer	110	102	43	121	83	75	94	244	170	94
Equipment Operator	135	-	135	168	154	151	176	177	164	278
Foreman	233	85	150	183	190	186	154	130	192	102
Laboratory worker	220	89	71	71	134	175	204	285	575	155
Manager	52	-	37	517	102	41	142	112	78	64
Non-rad job	125	-	48	96	105	72	93	226	181	33
Operator	305	129	151	234	369	371	640	516	413	298
Safety, security	168	75	265	59	65	83	415	273	119	183
Unknown	411	48	85	141	170	223	184	294	292	248
Worker	240	132	67	142	140	216	317	303	198	177
	Annual average beta exposure by year									
Job description	**1957**	**1958**	**1959**	**1960**	**1961**	**1962**	**1963**	**1964**	**1965**	**1966**
Engineer	228	23	191	579	486	572	277	308	186	90
Equipment Operator	190	1	878	1170	710	788	283	279	514	190
Foreman	328	45	492	1293	804	919	1336	735	637	257
Laboratory worker	382	133	343	463	796	724	367	327	340	278
Manager	107	35	199	1160	1099	403	204	128	91	181
Non-rad job	248	135	123	378	538	204	224	243	142	50
Operator	761	274	1122	2642	2695	1648	1309	1018	884	297
Safety, security	198	60	94	170	301	463	107	98	197	91
Unknown	524	128	297	890	1427	1146	338	401	453	205
Worker	697	93	472	923	1070	1107	780	354	473	317

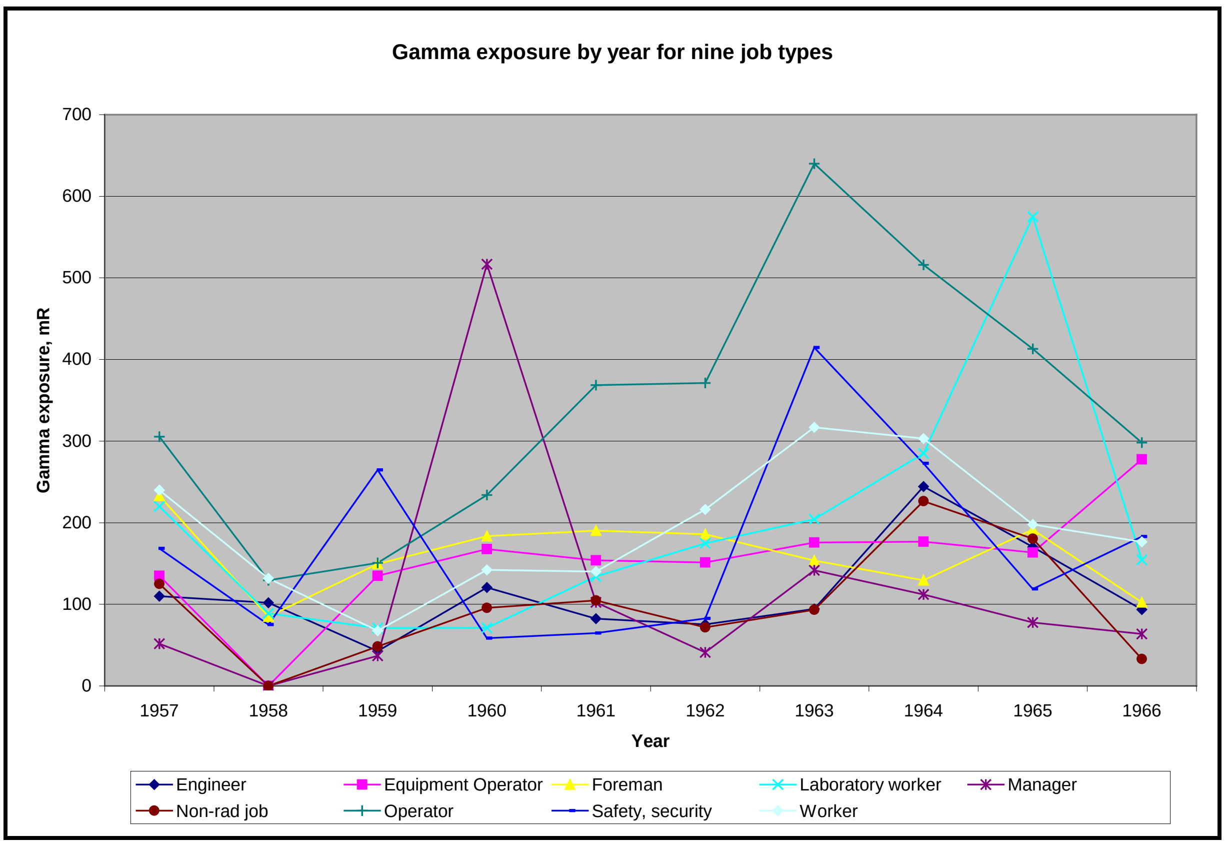

Figure 6-4. Average annual gamma exposure for various job categories.

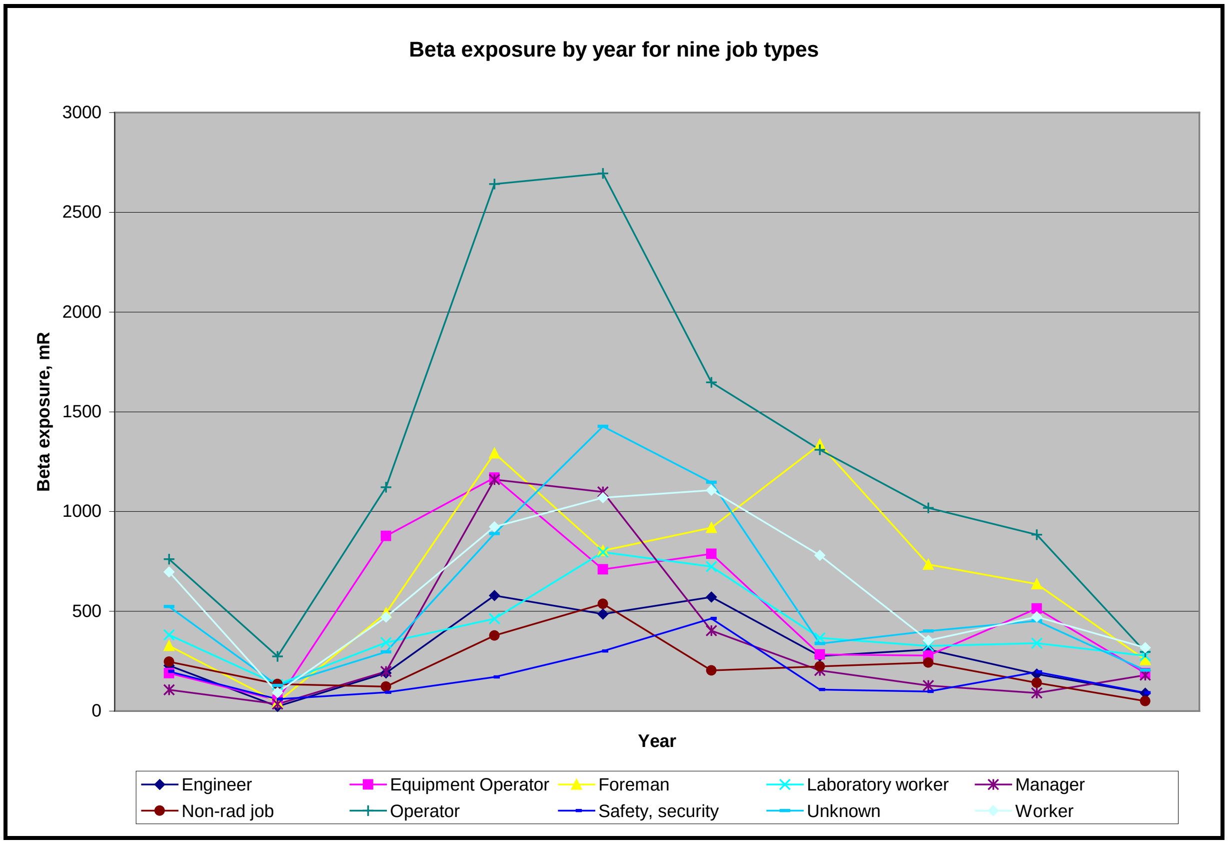

Figure 6-5. Average annual beta exposure for various job categories.

claimant-favorable 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%
30-250 keV		50%	100%	25%
>250 keV		50%	0%	75%

6.2.4.2 Neutron Dose

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 and UF_6 could have contributed dose to WSP workers. The analysis performed for the similar situation at Fernald (ORAU 2004a) 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. Natural uranium was addressed as well. 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 an upper 95% ratio limit of 0.23, should be applied in those areas where there is the potential for neutron dose from uranium fluoride compounds.
Table 6-10 lists energy distributions for WSP buildings.

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%
			>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%
202 A&B	Green Salt Tank Farm	None		

6.2.4.3 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 was also present at the site on an intermittent basis. Slightly enriched uranium (less than 1% ^{235}U by weight) was also present at times in the form of scrap metal or residues.

Table 6-10 (Continued). Energy distribution by building or area.

Building	Description	Radiation	Energy	Percentage
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%
		Neutron	0.1 – 2 MeV	100%
		Depleted U		
		Electron	>15 keV	100%
		Photon	30 – 250 keV	40%
			>250 keV	60%
		Neutron	0.1 – 2 MeV	100%
404	Metallurgical Pilot Plant	Natural U		
		Electron	>15 keV	100%
		Photon	30 – 250 keV	50%
			>250 keV	50%
		Neutron	0.1 – 2 MeV	100%
		Depleted U		
		Electron	>15 keV	100%
		Photon	30 – 250 keV	40%
			>250 keV	60%
		Neutron	0.1 – 2 MeV	100%
405A & B	Pilot Plant Maintenance	Natural U		
		Electron	>15 keV	100%
		Photon	30 – 250 keV	50%
			>250 keV	50%
		Neutron	0.1 – 2 MeV	100%
406	Warehouse	Natural Th		
		Electron	>15 keV	100%
		Photon	30 – 250 keV	25%
			>250 keV	75%
407	Laboratory	Natural U		
		Electron	>15 keV	100%
		Photon	30 - 250 keV	50%
			>250 keV	50%
		Neutron	0.1 - 2 MeV	100%
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	>15 keV	100%
		Photon	30 - 250 keV	50%
			>250 keV	50%
415	Process Incinerator	Natural U		
		Electron	>15 keV	100%
		Photon	30 - 250 keV	50%
			>250 keV	50%
417	Paint Shop	None		
426	Water Tower	None		
427	Primary Sewage Treatment Plant	none		
428	Fuel Gas Plant	None		

Table 6-10 (Continued). Energy distribution by building or area.

Building	Description	Radiation	Energy	Percentage
429	Water Reserve Facilities	None		
430	Ambulance Garage	None		
43l	Laboratory Sewer Sampler	Natural U		
		Electron	>15 keV	100%
		Photon	30 - 250 keV	50%
			>250 keV	50%
		Neutron	0.1 - 2 MeV	100%
432	Main Sewer Sampler	None		
437	Records Retention Building	None		
439, 443	Fire Training and Storage Building	None		
441	Cylinder Storage	None		

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.

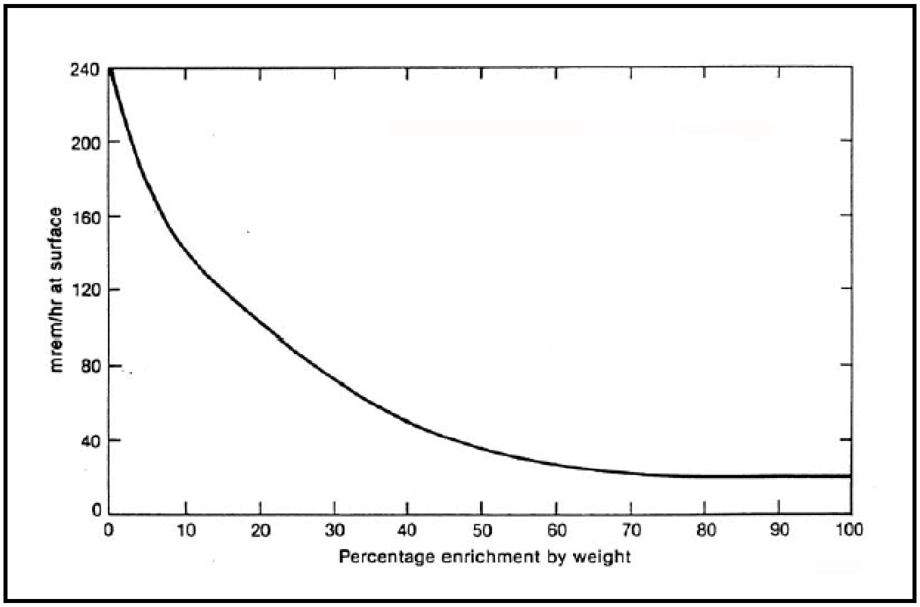

Figure 6-6. Estimated beta dose rate at surface of uranium metal at various enrichment levels (DOE 2001).

Processes that separate and sometimes concentrate beta-emitting uranium progeny are not uncommon in U.S. Department of Energy (DOE) uranium facilities. Surface beta dose rates on the order of 1 to 20 rad/hour 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 (Mason 1955). 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.

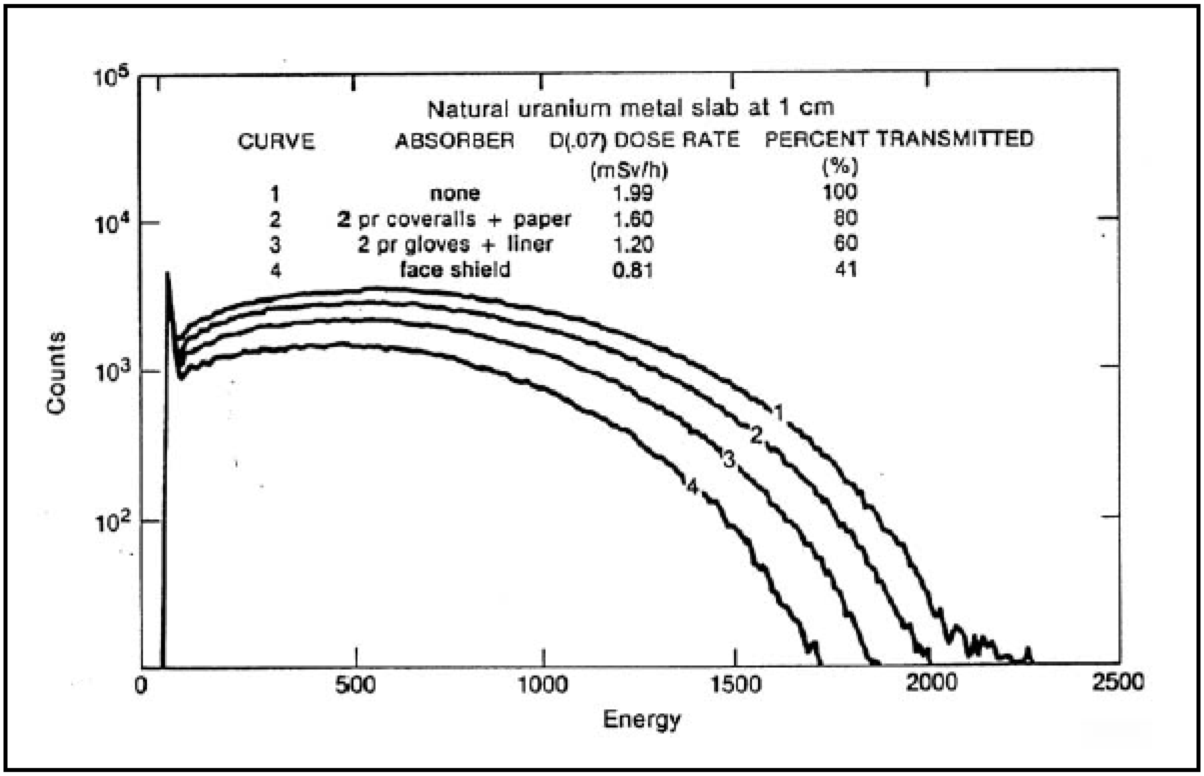

Figure 6-7. Shallow dose rate from natural uranium slab (DOE 2001).

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 to 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.

6.2.4.4 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.

6.2.4.5 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 as that used at Hanford and Fernald. A Pacific Northwest National Laboratory study of this two-element dosimeter identified a detection level of about 40 mR at the upper 95% confidence level for radium gamma radiation (ORAU 2004b). The Fernald TBD (ORAU 2004a) cites a minimum detection limit of 30 to 40 mrem, but it does not give a source for that information. The MCW St. Louis Plant TBD (ORAU 2003a) cites records in which gamma dose results are shown as "50*" where the asterisk refers to a footnote that

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		1997	$H_p(10)$
1958	R	1968	R	1978		1988		1998	$H_p(10)$
1959	R	1969	R	1979		1989		1999	$H_p(10)$
1960	R	1970		1980		1990		2000	$H_p(10)$
1961	R	1971		1981		1991			
1962	R	1972		1982		1992	$H_p(10)$		
1963	R	1973		1983		1993	$H_p(10)$		
1964	R	1974		1984		1994	$H_p(10)$		
1965	R	1975		1985		1995	$H_p(10)$		
1966	R	1976		1986		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		1997	*H'(0.07)*
1958	rad	1968	rad	1978		1988		1998	*H'(0.07)*
1959	rad	1969	rad	1979		1989		1999	*H'(0.07)*
1960	rad	1970		1980		1990		2000	*H'(0.07)*
1961	rad	1971		1981		1991			
1962	rad	1972		1982		1992	*H'(0.07)*		
1963	rad	1973		1983		1993	*H'(0.07)*		
1964	rad	1974		1984		1994	*H'(0.07)*		
1965	rad	1975		1985		1995	*H'(0.07)*		
1966	rad	1976		1986		1996	*H'(0.07)*		

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 claimant-favorable LOD for the WSP film dosimeter of 50 mR gamma and 80 mrep beta. Landauer (the 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 LODs for WSP dosimeters by year.

Year	LOD	Year	LOD	Year	LOD	Year	LOD	Year	LOD
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		

6.2.4.6 Exchange Frequency

Based on the historical evidence discussed in Section 6.1.3.1, it is claimant-favorable 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.

Table 6-14. Potential missed photon dose.

Period of use	Dosimeter	LOD	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 (minimum detection limit × exchange frequency) ÷ 2, from OCAS-IG-001 (NIOSH 2002).

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

Year	LOD	Year	LOD	Year	LOD	Year	LOD	Year	LOD
1957	80 mrep	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		

Table 6-16. Potential missed electron dose.

Period of use	Dosimeter	LOD	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 2002).

6.2.4.7 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 claimant-favorable.

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. Reconstructors should use dosimetry records, if available, to determine or estimate the exchange frequency. Using the methodology of NIOSH (2002), it is possible to develop a claimant-favorable 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	1500 mrep/wk

Table 6-18. AEC standards.

Type of exposure	Period of time	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 wk	3
Skin of whole body and thyroid	Year	30
	Calendar quarter or 13 consecutive wk	10
Hands and forearm, feet and ankles	Year	75
	Calendar quarter or 13 consecutive wk	25

Table 6-19. Dose limits (rem) based on exchange frequency.

Year	Limit	Exchange period		
		Biweekly	Monthly	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

6.2.4.8 Determination of Missed Dose

Determination of missed dose is performed using LOD/2 times the number of zero readings, as discussed in Section 2.1.2.2 of NIOSH (2002). If the number of zero readings is indeterminate, it can be estimated under the assumption that prorated dose limits were not exceeded.

6.2.4.9 Unmonitored Energy Range

The two-element film dosimeter used at WSP was similar to those used at other sites. The Savannah River Site TBD (ORAU 2003b) 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. This is the same approach taken in the Fernald Environmental Management Project Occupational External Dose TBD (ORAU 2004a).

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.

6.2.5 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. This factor is included in the overall bias provided elsewhere in this TBD.

6.2.6 Uncertainty

6.2.6.1 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. This study provides 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 (ORAU 2004b). The factors considered 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 (ORAU 2004a) is appropriate to use for the WSP dosimeter as well.

6.2.6.2 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% (see Table 6-20).

Table 6-20. Bias and uncertainty.

Site-specific dosimetry system	Bias magnitude and range		Uncertainty factors	
	Overall bias	**Range in bias**	**Systematic**	**Random[a]**
Two-element film 1957-1969 (photon)	1.0	0.5 - 1.6	1.2	1.4[b]
Two-element film 1957-1969 (electron)	1.0	0.5 - 1.6	1.2	
Landauer	1.0	NA	1.3[c]	1.3[c]

a. 95% upper (or lower) bound on normal distribution.
b. From Miller (1955).
c. Based on DOELAP performance standard.

REFERENCES

AEC (U.S. Atomic Energy Commission), 1963, *Standards for Radiation Protection*, Appendix 0524, Washington, DC, August 12.

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, February 11, Atomic Energy Commission, St. Louis Area Office, Missouri.

Belcher, F. H., 1966b, “Weldon Spring Health Protection Discussion,” memorandum to H. M. Roth (Director, Research and Development Division, Oak Ridge Operations), November 2, Atomic Energy Commission, St. Louis Area Office, Missouri.

Brandner, K. E., 1956a, “Film Badge Procedures for Transfers to Weldon Spring and New Hires for Weldon Spring,” memorandum to M. G. Mason, October 26, 1956, Mallinckrodt Chemical Works, Uranium Division, St. Louis, Missouri.

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.

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

Burr, R. H, 1959a, “Exchange of Turret Lathe Operators Film Badges,” memorandum to W. L. Utnage, January 26, 1959, Mallinckrodt Chemical Works, Uranium Division, St. Louis, Missouri.

Burr, R. H, 1959b, “Exchange of Film Badge Boards on January 30, 1959,” memorandum to W. L. Utnage, January 29, 1959, Mallinckrodt Chemical Works, Uranium Division, St. Louis, Missouri.

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.

DOE (U.S. Department of Energy), 1994, *External Dosimetry Technical Basis Manual: Weldon Spring Site Remedial Action Project*, DOE/OR/21548-44-1, Revision 0, Oak Ridge Operations Office, Oak Ridge, Tennessee, April.

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

DOE (U.S. Department of Energy), 2001, *Guide of Good Practices for Occupational Radiological Protection in Uranium Facilities*, DOE-STD-1136, Change Notice No. 3, Washington, D.C.

Dupree, E. E., J. P. Watkins, J. N. Ingle, and J. A. Phillips, 1999. External Radiation Exposure and Mortality Among a Cohort of Uranium Processing Workers, Dupree Ellis, E. Watkins, J. P., Ingle, J. N., and Phillips, J. A., Oak Ridge Associated Universities, Oak Ridge, Tennessee, undated.

HEW (U.S. Department of Health, Education and Welfare), 1970, "*Radiological Health Handbook*," Public Health Service, Food and Drug Administration, Bureau of Radiological Health, Rockville Maryland.

Ingle, N., 1998, "Mallinckrodt Chemical Works Dose Estimate Methodology," memorandum to Dr. Betsy (E.E.) Dupree, Oak Ridge Associated Universities, from N. Ingle, February 4, Delta-21 Resources, Inc., location unknown.

MCW (Mallinckrodt Chemical Works), 1958, "Weldon Spring Plant Film Badge Program," memorandum to W. L. Utnage, no date, Uranium Division, Health and Safety Department, Weldon Spring, Missouri.

MCW (Mallinckrodt Chemical Works), 1956, *Film Badge, Technique and Calibration*, November 1, Uranium Division, St. Louis, Missouri.

MCW (Mallinckrodt Chemical Works), 1965, *Summary of Health Protection Practices (Revised 1965)*, Uranium Division, St. Louis, Missouri.

MCW (Mallinckrodt Chemical Works), undated, *Personnel External Radiation Monitoring Program* Uranium Division, St. Louis, Missouri.

Mason, M. G., 1955, *Mallinckrodt Chemical Works Health Program: Policies, Status and Summary*, February 21.

Miller, J. W. 1955. Investigation of Film Badge Standards Calibration Data. Memo to M. G. Mason. Mallinckrodt Chemical Works, St. Louis, Missouri, February 3, 1955.

Miller, J. W., 1956, "Summary of the Mallinckrodt Chemical Works Film Badge Program," memorandum to K. E. Brandner, June 16, Mallinckrodt Chemical Works, Uranium Division, St. Louis, Missouri.

NIOSH (National Institute for Occupational Safety and Health), 2002, *External Dose Reconstruction Implementation Guideline*, OCAS-IG-001, Rev. 1, Office of Compensation Analysis and Support, Cincinnati, Ohio.

NRC (National Research Council), 1989, *Film Badge Dosimetry in Atmospheric Nuclear Tests*, National Academy Press, Washington D.C.

ORAU (Oak Ridge Associated Universities), 2003a, *Technical Basis Document: Basis for Development of an Exposure Matrix for the Mallinckrodt Chemical Company St. Louis Downtown Site, St. Louis Missouri, Period of Operation: 1942-1958*, ORAUT-TKBS-0005, Rev. 00, Oak Ridge, Tennessee, October.

ORAU (Oak Ridge Associated Universities), 2003b, *Technical Basis Document for the Hanford Site – Occupational External Dosimetry*, ORAUT-TKBS-0006-6, Rev. 01, Oak Ridge, Tennessee, January 9.

ORAU (Oak Ridge Associated Universities), 2004b, *Technical Basis Document for the Savannah River Site*, ORAUT-TKBS-0004, Rev. 02, Oak Ridge, Tennessee, October 29.

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

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

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.

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.

GLOSSARY

U.S. Atomic Energy Commission (AEC)
Original agency established for nuclear weapons and power production; a predecessor to the U.S. Department of Energy and the Energy Research and Development Administration.

beta dose
A designation (i.e., beta) on some external dose records referring to the dose from less-energetic beta, X-ray, and/or gamma radiation (see open window, or shallow dose).

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

deep absorbed dose
The absorbed dose at the depth of 1.0 cm in a material of specified geometry and composition.

dose equivalent (*H*)
The product of the absorbed dose *D*, the quality factor *Q*, and any other modifying factors. The special unit is the rem. When *D* is in gray, *H* is in sieverts, where 1 sievert is 100 rem.

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

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

dosimetry system
A system used to assess dose equivalent from external radiation to the whole body, skin, or extremities. This includes the fabrication, assignment, and processing of dosimeters as well as interpretation and documentation of the results.

exchange period (frequency)
Period (weekly, semimonthly, monthly, quarterly, etc.) for routine exchange of dosimeters.

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

extremity
That portion of the arm extending from and including the elbow through the fingertips and that portion of the leg extending from and including the knee and patella through the tips of the toes.

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

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

film density
See optical density.

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

fission
The splitting of a heavy atomic nucleus accompanied by the release of energy.

fissionable
Material capable of undergoing fission.

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

ionizing radiation
Electromagnetic or particulate radiation capable of producing charged particles through interactions with matter.

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

neutron
A basic particle that is electrically neutral and weighs nearly the same as the hydrogen atom.

open window
Designation on film dosimeter reports that implies the use of little (i.e., only security credential) shielding. Commonly used to label the film response corresponding to the open window area.

operating area
Designation of major onsite operational work areas.

optical density
The quantitative measurement of photographic blackening; density defined as D = Log10 (Io/I).

personal dose equivalent *Hp(d)*
Represents the dose equivalent in soft tissue below a specified point on the body at an appropriate depth *d*. The depths selected for personnel dosimetry are 0.07 and 10 millimeters for the skin and body, respectively. These are noted as *Hp(0.07)* and *Hp(10)*, respectively.

photon
A unit or "particle" of electromagnetic radiation consisting of X- or gamma rays.

photon X-ray
Electromagnetic radiation of energies between 10 and 100 kilovolts-electron whose source can be an X-ray machine or radioisotope.

quality factor, *Q*
A modifying factor used to derive dose equivalent from absorbed dose.

radiation
Alpha, beta, neutron, and photon radiation.

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

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

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

roentgen
A unit of exposure to gamma (or X-ray) radiation. It is defined precisely as the quantity of gamma (or X-) rays that produces a total charge of 2.58×10^{4} coulomb in 1 kilogram of dry air. An exposure of 1 roentgen is approximately equivalent to an absorbed dose of 1 rad in soft tissue for higher (about 100 kilovolts-electron or more) energy photons.

shallow absorbed dose (*Ds*)
The absorbed dose at a depth of 0.007 centimeter in a material of specified geometry and composition.

shallow dose equivalent (*Hs*)
Dose equivalent at a depth of 0.007 centimeter in tissue.

shielding
Any material or obstruction that absorbs (or attenuates) radiation and thus tends to protect personnel or materials from radiation.

skin dose
Absorbed dose at a tissue depth of 7 milligrams per square centimeter.

whole-body dose

Commonly defined as the absorbed dose at a tissue depth of 1.0 centimeter (1,000 milligrams per square centimeter); however, also used to refer to the recorded dose.

X-ray

Ionizing electromagnetic radiation of external nuclear origin.

ATTACHMENT A
Example Reports

LIST OF FIGURES

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/m^3
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.

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.

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.

JANUARY 15 1964

ANNUAL
PERSONNEL EXTERNAL RADIATION
EXPOSURE REPORT
YEAR 1963

GROUP-UNIT 0308 [redacted] AGE 33 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.

[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

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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	m γ	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.

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.

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	24.53	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.