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ACRONYMS AND ABBREVIATIONS

CFR	Code of Federal Regulations
EEOICPA	Energy Employees Occupational Illness Compensation Program Act of 2000
HVL	half value layer
ICRP	International Commission on Radiological Protection
IREP	Interactive RadioEpidemiological Program
kerma	initial kinetic energy of charged particles liberated by uncharged ionizing radiation per unit mass
LAT	lateral
NCRP	National Council on Radiation Protection and Measurements
NIOSH	National Institute for Occupational Safety and Health
PA	posterior-anterior
SID	source-to-image distance
SSD	source-to-skin distance
TBD	technical basis document
U.S.C.	United States Code
WSP	Weldon Spring Plant

3.1 OCCUPATIONAL MEDICAL DOSE

As part of the requirements for employment at the Weldon Springs Plant (WSP) from 1955 through 1966 (the WSP operational period) and from 1986 through the present, all employees received periodic physical examinations. These could include annual radiographic examinations of the chest, as directly and indirectly referenced in site-related reports (Mason 1955; Quigley and Mason 1963) and periodic chest x-ray examinations for remediation workers exposed to asbestos or using respirators (Lopez 2004). The National Institute of Occupational Safety and Health (NIOSH), in its role to reconstruct occupational dose under the Energy Employees Occupational Illness Compensation Program Act of 2000 (EEOICPA), 42 U.S.C. §§ 7384-7385, has classified diagnostic medical x-rays administered in conjunction with routine or special physical examinations required for employment as occupational exposures (NIOSH 2002). This technical basis document (TBD) discusses medical exposures required as a condition of employment; it does not include diagnostic and therapeutic procedures because they were not required for employment. In addition, this TBD provides dose estimates for workers who might have been present between 1966 and 1985, including security personnel who might have received x-ray examinations as a requirement of employment. It also provides estimates for post-1985 remediation personnel.

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 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 EEOICPA (42 U.S.C. § 7384l (5) and (12)).

The following subsections of this TBD describe the methodology used to estimate absorbed dose from x-ray exposure for WSP workers. In the absence of available data, assumptions are claimant-favorable. Section 3.1.1 provides introductory text. Section 3.1.2 describes x-ray examination frequency at WSP. Section 3.1.3 provides information on equipment and techniques used at WSP, including assumptions necessitated by lack of protocol, measurement, or records data. Section 3.1.4 provides organ dose estimates by calendar year and type of x-ray. Section 3.1.5 documents uncertainties.

3.1.1 Introduction

As described in *Protection of the Patient in Diagnostic Radiology* (ICRP 1982), the amount of energy absorbed in the body and its distribution in specific organs can be determined by measurement or calculation. Absorbed dose in tissue, measured in units of gray (Gy), is equal to the energy absorbed per unit mass at a point in the human body. The current international system of units expresses this quantity in air kerma.

The radiation dose received in a given examination varies widely throughout the body. Doses are highly dependent on the technical factors employed, characteristics of the equipment, collimation of the beam, and number of films taken. The general equation for total annual occupational medical dose provided by NIOSH (2002) guidelines is:

$$Dom = \Sigma nDi \qquad (3–1)$$

where

Dom = occupational medical dose
n = number of exams in a calendar year
Di = dose from the x-ray procedure

The NIOSH guidelines state that medical records should contain the dates, types, and number of x-ray examinations, and that if there is no known information about the energy spectra, values should conservatively be assumed to be in the 30- to 250-kV photon range (a claimant-favorable assumption). The guidance states that the uncertainty distribution about each x-ray procedure is assumed to follow a normal distribution, with Dom being the mean dose.

3.1.2 Examination Frequency

The frequency and type of x-ray examinations are referenced in reports for WSP workers from 1955 through 1966 (Thornton and Johnson 1965, Mallinckrodt 1965). Neither a protocol for the frequency of chest x-ray examinations as a function of job category nor a reference to any other type of x-ray examination has been located. However, the references clearly indicate that chest x-ray examinations were performed annually from 1955 through 1966, and medical records indicate that both posterior-anterior (PA) and lateral (LAT) views were taken. Therefore, the analysis for this TBD assumed annual PA and LAT chest x-ray examinations for all employees, and considered no other view. A review of pre-1970 files indicates that, approximately 30% of the time, workers received two sets of chest x-rays in a period of 9 months or less (excluding x-rays for termination of employment); the files do not provide reasons for this. The analysis assumed that the same frequency of chest x-ray examinations would have been used for security personnel present from 1966 through 1985.

For the post-1985 remediation period, some workers might have received chest x-ray examinations; such examinations might not have been mandatory on an annual basis. Specifically, respirator users or asbestos workers were probably required to have chest x-rays for the first medical examination, after which x-ray examinations occurred every 2 or 5 years depending on the work performed; this analysis assumed that PA and LAT chest x-rays were performed at each examination (Lopez 2004).

3.1.3 Equipment and Techniques

The analysis assumed that WSP radiological practices followed standards of medical practice to minimize dose to the patient; however, the type of equipment, technique factors, and machine calibrations are not known. According to Thornton and Johnson (1965), a medical x-ray unit was present on the site; a report dated January 1966 indicates that it was used regularly and that x-rays were read by an offsite radiologist. Quigley and Mason (1955) indicate that chest x-ray examinations occurred at Barnes Hospital Laboratories, presumably prior to the installation of onsite equipment. To date, there has been no indication in either the available protocol or in worker medical files that photofluorography was ever used at WSP.

This TBD provides organ dose estimates from occupational x-ray examinations administered at WSP from 1955 through 1966 (pre-1970), 1970 to 1985, and post-1985 using default dose estimates from *Technical Information Bulletin* [TIB]*: Dose Reconstruction from Occupationally Related Diagnostic X-ray Procedures* (ORAU 2005). For the years before 1970, the default values assume minimal beam collimation and a half-value layer (HVL) of 2.5 mm Al. For 1970 to 1985, the default values assume that the beams were collimated and the HVL was 2.5 mm Al. For post-1985, the default values assume collimation and an HVL of 4.0 mm Al.

For all periods, the analysis assumed that PA and LAT chest x-rays occurred at hire, at each annual physical examination, and at termination of employment, as evidenced by available protocols. Records of machine settings are not available so this TBD uses default estimates for LAT and PA chest x-rays from ORAU (2005).

Efforts will continue to locate related WSP information. Until more accurate records are located, these assumptions provide the only available estimates.

3.1.4 Organ Dose Estimates

This section discusses organ dose estimates. Section 3.1.4.1 describes the methodology used to estimate these doses, and Section 3.1.4.2 discusses results.

3.1.4.1 Parameters and Estimation Method

Measured air kerma data should be the basis or organ estimates, if available. If these data are not available, air kerma rates can be estimated from Figure 3-1. Since this information has not yet been found for WSP, organ dose estimates are based on the values in ORAU 2005. Default entrance kerma for PA and LAT chest x-rays from ORAU 2005 are presented in Table 3-1. DCFs are listed in Table 3-2.

Table 3-1. Default entrance kerma by procedure and time period (ORAU 2005)

Period	Entrance kerma, cGy, PA chest	Entrance kerma, cGy, LAT chest
Pre-1970	0.2	0.5
1970-1985	0.1	0.25
Post-1985	0.05	0.13

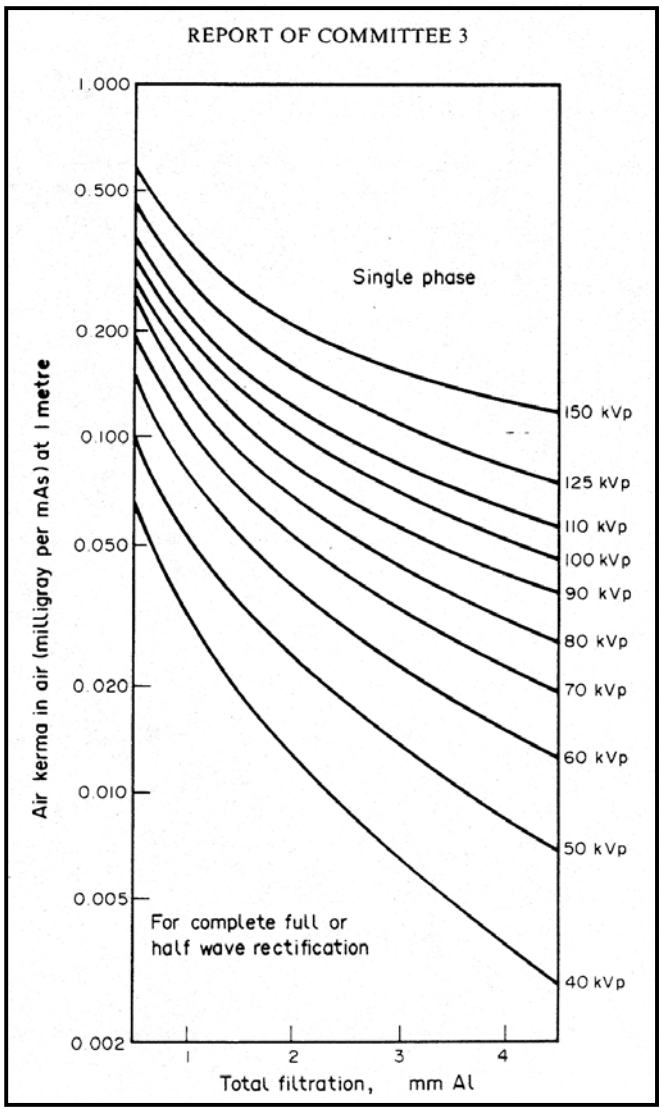

Figure 3-1. Kerma in air at 1 meter from X-ray source as a function of total filtration for various values of tube potential (from ICRP 1982).

The ICRP tables used to estimate absorbed dose (ICRP 1982) do not include all the organs included in the Interactive RadioEpidemiological Program (IREP) computer program. For organs in IREP but not identified in the ICRP tables, the dose conversion coefficient that is anatomically closest to the IREP-specified organs can be used to estimate dose. For example, the factor for lung can be applied to all other organs in the thoracic cavity, such as the esophagus and bone surface. For abdominal organs (bladder, colon), use the dose coefficient for ovaries. Such dose assignment will be conservative because the analog organ is more shielded than the reference organ. Table 3-3 lists analogs for IREP organs, as originally presented in ORAU 2005.

Table 3-2. Modified ICRP dose conversion factors; absorbed dose (1 mGy) for organs at various Al HVL for chest radiography (ORAU 2005)[a].

Organ	Dose conversion factors					
	Pre-1970 (2.5-mm Al HVL)		1970-1985 (2.5-mm Al HVL)		Post-1985 (4.0-mm Al HVL)	
	LAT	PA	LAT	PA	LAT	PA
Thyroid	137	174 [b]	115	32	164	78
Eye/brain	137	32	115	32	164	78
Ovaries	N/A	N/A	0.6	1	2.5	5.2
Liver/gall bladder/ spleen	220	451	220	451	351	674
Urinary bladder	N/A	N/A	0.6	1	2.5	5.2
Colon/rectum	N/A	N/A	0.6	1	2.5	5.2
Testes	N/A	N/A	0.1	0.01	0.1	0.01
Lungs (male)	193	419	193	419	313	628
Lungs (female)	220	451	220	451	351	674
Thymus	220	451	220	451	351	674
Esophagus	220	451	220	451	351	674
Stomach	220	451	220	451	351	674
Bone surfaces	220	451	220	451	351	674
Remainder	220	451	220	451	351	674
Female breast	255	49	255	49	343	116
Uterus	N/A	N/A	0.6	1.3	2.1	5.2
Bone marrow (male)	37	92	37	92	76	178
Bone marrow (female)	29	86	29	86	59	172
Skin [c]	N/A	N/A	N/A	N/A	N/A	N/A

[a] Organ doses are presented in Table 4 for all organs.
[b] Per ORAU 2005, DCF for AP c-spine corrected for depth by 0.2
[c] Calculated using backscatter factor of 1.35 from NCRP Report 103, Table B-3 (ORAU 2005); see Table 4

Table 3-3. Analogs for IREP organs not specified in ICRP (1982).

Anatomical location	ICRP #34 reference organ	IREP organ analogues [a]
Thoracic cavity	Lung	Thymus, esophagus, stomach, bone surface, liver/ gall bladder, remainder organs
Abdominal cavity	Ovaries	Uterus, urinary bladder, colon/rectum
Head and neck	Thyroid	Eye/brain

[a] ORAU 2005

3.1.4.2 Organ Dose Estimates for WSP Workers

Table 3-4 lists default organ dose estimates from LAT and PA chest x-ray examinations for each period (pre-1970, 1970 to 1985, and post-1985). The estimates for exposure from chest x-rays for these periods are taken from default values as presented in Table 5 of ORAU 2005 while site-specific information is being obtained.

3.1.5 Uncertainties

As stated in ORAU (2003 and 2005), *error* is defined as deviation from the correct, true, or conventionally accepted value of a quantity, and *uncertainty* is defined in terms of the potential range

of a stated, measured, or assumed or otherwise determined value of a quantity. Error and uncertainty provide an indication of confidence in the dose estimates. Uncertainty, expressed in terms of a confidence level, is a more appropriate term than error, which implies that the actual value is known. Uncertainty, stated as a probability of falling within a stated range, includes precision and reproducibility of the measurement as well as accuracy (that is, how close the estimate comes to the actual value).

Table 3-4. Organ dose estimates for chest x-rays (rem) as presented in ORAU 2005.

[Period: Pre-1970]

Organ	Estimated dose[a,b,c] HVL = 2.5 mm Al (uncollimated)	
	LAT (rem)	PA (rem)
Thyroid	6.85E-02	3.48E-02
Eye/brain	6.85E-02	6.4E-03
Ovaries	1.3E-02[d]	2.5E-02[d]
Liver/gall bladder/spleen	1.10E-01	9.02E-02
Urinary bladder	1.3E-02[d]	2.5E-02[d]
Colon/rectum	1.3E-02[d]	2.5E-02[d]
Testes	2.5E-03[d]	5.00E-03[d]
Lungs (male)	9.65E-02	8.38E-02
Lungs (female)	1.1E-01	9.02E-02
Thymus	1.1E-01	9.02E-02
Esophagus	1.1E-01	9.02E-02
Stomach	1.1E-01	9.02E-02
Bone surfaces	1.1E-01	9.02E-02
Remainder	1.1E-01	9.02E-02
Female breast	1.28E-01	9.8E-03
Uterus	1.3E-02[d]	2.5E-02[d]
Bone marrow (male)	1.85E-02	1.84E-02
Bone marrow (female)	1.45E-02	1.72E-02
Skin[e]	6.75E-01	2.7E-01

[Period: 1975-1985]

Organ	Estimated dose[a,b,c] HVL = 2.5 mm Al (collimated)	
	LAT (rem)	PA (rem)
Thyroid	2.88E-02	3.20E-03
Eye/brain	2.88E-02	3.20E-03
Ovaries	1.50E-04	1.00E-04
Liver/gall bladder/spleen	5.5E-02	4.5E-02
Urinary bladder	1.50E-04	1.00E-04
Colon/rectum	1.50E-04	1.00E-04
Testes	2.5E-05	1.00E-06
Lungs (male)	4.83E-02	4.19E-02
Lungs (female)	5.50E-02	4.51E-02
Thymus	5.50E-02	4.51E-02
Esophagus	5.50E-02	4.51E-02
Organ	Estimated dose[a,b,c] HVL = 2.5 mm Al (collimated)	
	LAT (rem)	PA (rem)
Stomach	5.50E-02	4.51E-02
Bone surfaces	5.50E-02	4.51E-02
Remainder	5.50E-02	4.51E-02
Female breast	6.38E-02	4.90E-03
Uterus	1.50E-04[d]	1.30E-04[d]
Bone marrow (male)	9.25E-03	9.20E-03
Bone marrow (female)	7.25E-03	8.60E-03
Skin[f]	3.38E-01	1.35E-01

Table 3.4 (Continued). Organ dose estimates for chest x-rays (rem).

[Period: post - 1985]

Organ	Estimated dose HVL = 4.0 mm Al (collimated)	
	LAT (rem)	PA (rem)
Thyroid	2.13E-02	3.90E-03
Eye/brain	2.13E-02	3.90E-03
Ovaries	3.25E-04	2.60E-04
Liver/gall bladder/spleen	4.56E-02	3.37E-02
Urinary bladder	3.25E-04	2.60E-04
Colon/rectum	3.25E-04	2.60E-04
Testes	1.30E-05	5.00E-07
Lungs (male)	4.07E-02	3.14E-02
Lungs (female)	4.56E-02	3.37E-02
Thymus	4.56E-02	3.37E-02
Esophagus	4.56E-02	3.37E-02
Stomach	4.56E-02	3.37E-02
Bone surfaces	4.56E-02	3.37E-02
Remainder	4.56E-02	3.37E-02
Female breast	4.46E-02	5.80E-03
Uterus	2.73E-04	2.60E-04
Bone marrow (male)	9.88E-03	8.90E-03
Bone marrow (female)	7.67E-03	8.60E-03
Skin[f]	1.82E-01	7.00E-02

a. SID 183 cm.
b. Image receptor size 35.6 cm by 43.2 cm.
c. Modified from Webster and Merrill (1957), as presented in ORAU (2005).
d. Modified from Webster and Merrill (1957) as presented in ORAU (2005)
e. Calculated in ORAU (2005) using backscatter factor of 1.35 from NCRP (1989, Table B-3).
f. Calculated in ORAU (2005) using backscatter factor of 1.40 from NCRP (1989, Table B-3).

Although many factors can introduce uncertainty and error into x-ray exposures, five factors contribute the most uncertainty to the dose estimate: measurement error, variation in applied kilovoltage, variation in beam current, variation in exposure time, and SSD. Film speed, the use of screens, or the use of grids would not affect the beam output intensity. The lack of historical records for these measurements for most years at WSP introduces a large uncertainty into the dose estimates that cannot be readily quantified, although there is no apparent reason to believe that practices at the Plant or its medical subcontractors were different from those at other facilities or from recommended standards of the medical community at the time. Therefore, the use of default estimates and reliance on information from other DOE sites when site-specific information was unavailable is likely to approximate x-ray performance at WSP closely. The following estimates of uncertainty associated with x-ray exposure are from ORAU (2005), which this TBD analysis relied on for default information in the absence of site-specific records.

ORAU (2005) reports that x-ray doses are derived largely from actual measurements of x-ray machine output with R-meters or similar ionization chamber devices. Reportedly, these typically had an uncertainty of $\pm$2% for photon energies below 400 keV, if properly calibrated and used. Although more current machinery could have a smaller uncertainty, +2% is assumed to be conservative.

Variation in applied voltage generally falls within ±5% of the machine setting. Beam intensity is approximately proportional to the 1.7 power of the kilovoltage, resulting in an uncertainty of approximately +9% in relation to beam intensity for voltages in the 110- to 120-kVp range. Variations in tube current are normal and generally small. As the tube current drops, beam intensity falls in direct proportion. Large decreases in beam output would be readily detectable and would indicate the need for machine maintenance or, as a temporary measure, an increase in the current or voltage to provide the necessary intensity for proper radiography. ORAU (2005) estimates the variation in tube current to be approximately ± 5% for this parameter.

Exposure time can significantly affect the dose received from radiography (exposure times are a fraction of second). Even a small variation in exposure time due to timer error can significantly change beam output. Because early x-ray machine timers are known to have been inaccurate, ORAU (2003 and 2005) assume uncertainty in beam output due to timers to be ±25%.

SSD can contribute to variability because the entrance skin exposure is determined by this distance. Variations result from accuracy of positioning as well as patient size (thickness). As expressed in ORAU (2003 and 2005), this is generally thought to vary by no more than a few centimeters, with an upper limit of 7.5 cm (±10%).

A potentially large source of uncertainty for WSP is the number and type of x-rays taken. As noted above, reports indicate the performance of only an annual chest x-ray examination, but no official protocol has been found that would rule out the possibility of other x-ray views or more frequent chest examinations. At this time, dose reconstructors should assume an annual chest x-ray for 1958 through 1964.

Consistent with ORAU (2003 and 2005), the TBD analysis calculated the statistical root mean square to estimate total uncertainty. The root mean square is the square root of the sum of the squares of the individual uncertainty values, and equals 28.9%. An estimate of 30% uncertainty is larger than the default NIOSH guidance standard deviation recommendation of 20% (NIOSH 2002). Therefore, dose reconstructors should multiply all final estimates by 1.3 to account for uncertainty, conservatively assuming that all variables acted to increase dose.

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