ORAU TEAM
Dose Reconstruction
Project for NIOSH

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PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
08/22/2005	00	New technical basis document for the Lawrence Livermore National Laboratory – Occupational Medical Dose. First approved issue. Initiated by Jay J. Maisler.
10/26/2005	00 PC-1	First approved page change. Page change initiated to incorporate recent direction from NIOSH to include DOL review comments on page 5. No sections were deleted. Retraining is not required. Initiated by Jay J. Maisler. Approval: Signature on File 10/14/2005 Jay J. Maisler, TBD Team Leader Signature on File 10/13/2005 Judson L. Kenoyer, Task 3 Manager Signature on File 10/16/2005 Richard E. Toohey, Project Director Signature on File 10/26/2005 James W. Neton, Associate Director for Science
08/27/2010	01	Revised to include organ dose from lateral and oblique chest projections that were taken on some workers but not initially listed in the records submitted by LLNL. Also included are skin doses for all projections and periods. Incorporates formal internal and NIOSH review comments. Constitutes a total rewrite of the document. Training required: As determined by the Task Manager. Initiated by Ralph W. Kenning.

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ACRONYMS AND ABBREVIATIONS

CFR	Code of Federal Regulations
cm	centimeter
DOE	U.S. Department of Energy
EEOICPA	Energy Employees Occupational Illness Compensation Program Act
ENSD	Entrance Skin Dose
EXSD	Exit Skin Dose
ESE	entrance skin exposure
FDA	Food and Drug Administration
Gy	gray
HVL	half-value layer
keV	kiloelectron-volt (1,000 electron volts)
kVp	kilovolts-peak
LAT	lateral
LLNL	Lawrence Livermore National Laboratory
m	meter
mA	milliampere
mm	millimeter
mR	milliroentgen
mrem	millirem
NCRP	National Council on Radiation Protection and Measurements
NIOSH	National Institute for Occupational Safety and Health
OBL	oblique
PA	posterior-anterior
POC	probability of causation
R	roentgen
RAO	right anterior oblique
RSD	Remote Skin Dose
s	second
SSD	source-to-skin distance
TBD	technical basis document
U.S.C.	United States Code
§	section, sections

3.1 INTRODUCTION

Technical basis documents (TBDs) and site profile documents are not official determinations made by the National Institute for Occupational Safety and Health (NIOSH) but are rather general working documents that provide historic background information and guidance to assist in the preparation of dose reconstructions at particular sites or categories of sites. They will be revised in the event additional relevant information is obtained about the affected site(s). These documents may be used to assist NIOSH staff in the completion of the individual work required for each dose reconstruction.

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

For employees of DOE or its contractors with cancer, the DOE facility definition only determines eligibility for a dose reconstruction, which is a prerequisite to a compensation decision (except for members of the Special Exposure Cohort). The compensation decision for cancer claimants is based on a section of the statute entitled "Exposure in the Performance of Duty." That provision [42 U.S.C. § 7384n(b)] states that an individual with cancer "shall be determined to have sustained that cancer in the performance of duty for purposes of the compensation program if, and only if, the cancer … was at least as likely as not related to employment at the facility [where the employee worked], as determined in accordance with the POC [probability of causation[1]] guidelines established under subsection (c) …" [42 U.S.C. § 7384n(b)]. Neither the statute nor the POC guidelines (nor the dose reconstruction regulation, 42 CFR Part 82) define "performance of duty" for DOE employees with a covered cancer or restrict the "duty" to nuclear weapons work (NIOSH 2007).

The statute also includes a definition of a DOE facility that excludes "buildings, structures, premises, grounds, or operations covered by Executive Order No. 12344, dated February 1, 1982 (42 U.S.C. 7158 note), pertaining to the Naval Nuclear Propulsion Program" [42 U.S.C. § 7384l(12)]. While this definition excludes Naval Nuclear Propulsion Facilities from being covered under the Act, the section of EEOICPA that deals with the compensation decision for covered employees with cancer [i.e., 42 U.S.C. § 7384n(b), entitled "Exposure in the Performance of Duty"] does not contain such an exclusion. Therefore, the statute requires NIOSH to include all occupationally derived radiation exposures at covered facilities in its dose reconstructions for employees at DOE facilities, including radiation exposures related to the Naval Nuclear Propulsion Program. As a result, all internal and external occupational radiation exposures are considered valid for inclusion in a dose reconstruction. No efforts are made to determine the eligibility of any fraction of total measured exposure for inclusion in dose reconstruction. NIOSH, however, does not consider the following exposures to be occupationally derived (NIOSH 2007):

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

[1] The U.S. Department of Labor is ultimately responsible under the EEOICPA for determining the POC.

3.2 OCCUPATIONAL MEDICAL X-RAYS

Chest X-ray examinations have been prescribed for occupational health screening by Health Services Department clinicians at Lawrence Livermore National Laboratory (LLNL) beginning in 1952 (Author unknown 1987, pg. 23; Noonan 2002). The purpose of this TBD is to develop estimates of doses from occupational medical X-rays to the lungs and other organs of the body. These doses, determined for radiographic chest examinations during different periods at LLNL, are based on the operating parameters of the machines and the conditions of exposure, insofar as these are known.

From 1952 until about 1990, baseline X-rays were required for all preemployment evaluations (Noonan 2002; Schaer 1964). The earliest document found mentions the preemployment chest X-ray policy in existence in 1964 (Schaer 1964). This document also mentions that the periodic physical examinations, without specific mention of X-rays during these, occurred no more frequently than on an annual basis, and in many cases occurred on a biennial frequency. A sample of LLNL claim file records and an analysis of the chest X-ray frequency in relation to the number of years worked shows that, on average, workers were X-rayed about every 4 years [1]. In the absence of records, dose reconstructors should assume a biennial chest X-ray frequency.

All the historical documents state that a single, posterior-anterior (PA) chest projection comprised the preemployment X-ray screen (Noonan 1991, 1992; Thomas 1991). For the most part, the claim file records support these statements [2]. While it appears that not all chest projections in addition to the PAs that were performed on workers were initially reported by LLNL, the additional records LLNL has provided since they were made aware of this issue show that about 40% contain differences from the first submission. In some cases, these are lateral (LAT) chest projections that were performed at the same time as the PA, and therefore should be included in dose reconstruction [3]. However, in several cases, the second submittal from LLNL contains what appear to be individual specific diagnostic (as opposed to screening) projections such as right LAT chests, oblique (OBL) chests, or lordotic chests that were performed a week or two following the PA chest screening exam. None of these additional projections appear to have occurred frequently enough in the population of LLNL workers to consider including dose from them for all workers as a default assumption when records are not available, nor should the dose from these be included in dose reconstruction when records show that they clearly were performed as additional projections during a followup or “call back” visit [4]. The few lumbar spine records in claim files do not appear to have been performed for screening since they were performed on workers whose job description probably did not include heavy lifting (i.e. scientists and engineers) and because they were performed mid career as opposed to pre-employment [5]. Therefore, the dose from lumbar spines should not be included in dose reconstruction.

Starting around 1990, historical records suggest that periodic X-ray screening would be performed on an as-needed basis (LLNL, 1991; Van Pelt 1990). *LLNL Health Services Department Radiography Program, March 1991* (LLNL, 1991), provides the following information:

> *Requisition of X-ray studies for the purpose of diagnostic information should be based on clinical evaluation. Diagnostic X-ray examinations will be requested after an appropriate medical history and physical examination has been performed, in accordance with reasonable medical practice and occupational guidelines. Diagnostic objective, relevant medical history and X-ray procedure requested will be recorded on the radiographic request form. … Based on the unique nature of the work performed at LLNL, a pre-employment baseline PA [posterior-anterior] chest X-ray examination is required. This film may be done at the time of pre-employment examination or a copy of a previous film or report may be requested and kept on file. Medical surveillance programs may mandate periodic chest X-rays. Periodic chest X-ray examinations*

unrelated to job exposure will not be done routinely but may be ordered by the examiner if clinically indicated.

No evidence of photofluorography at LLNL has been found in the historical records, claim file records, or a review of film archives performed by previous TBD authors [5]. No evidence has been found in the historical records or claim file records of X-rays taken at the time of termination. Table 3-1 contains a summary of the frequency of occupational chest X-ray screening at LLNL and can be used by the dose reconstructors in the absence of claim file records.

Table 3-1. Frequency of occupational chest X-ray screening.[a]

Period	Workers	Frequency	Chest projections
1952 to 1990	All employees	Preemployment	PA
	All employees	Biennially	PA
	Asbestos workers	≥50 years old: Biennially	PA, LAT, RAO
		40-49 years old: every 3 years	PA, LAT, RAO
		<40 years old: every 5 years	PA, LAT, RAO
1990–present	All employees	Preemployment	PA
	Employees subject to inhalation exposure	Biennially	PA
	Asbestos workers	≥50 years old: Biennially	PA, LAT, RAO
		40-49 years old: every 3 years	PA, LAT, RAO
		<40 years old: every 5 years	PA, LAT, RAO

a. Author unknown (1987); LLNL (1991).

3.3 EQUIPMENT AND TECHNIQUES

Table 3-2 lists the medical X-ray machines used at LLNL, as well as can be determined from existing records. Reported data for entrance skin exposures (ESEs) for PA chest examinations were found on all three systems and are included in Table 3-2.

Table 3-2. LLNL X-ray equipment.

Period	Equipment and operating parameters
1952-1969	Equipment unknown, Doses from ORAUT-OTIB-0006 (ORAUT 2005)
1970–1980	Fischer X-ray machine: 100 kVp, 100 mA, 1/20 s, filtration of 3 mm Al, effective energy 32 keV, "satisfactory" collimation, measured ESE = 19 mR at SSD = 157 cm (Graham and Williams 1975; Myers and Williams 1979)
1981–1990	Xonics: Stationary general-purpose X-ray system, phototiming, Kodak M-35 film processor using Kodak XRP chemistry, blue-light-sensitive film, measured ESE = 45 mR (Shingleton 1985; de Castro 1989; Van Pelt 1990)
1991– 1992	Upgraded Xonics system: Blue-light-sensitive film replaced with green-light-sensitive Kodak T-MAT G and T-MAT L films, new cassette holders with compatible emitting screens, manual control techniques applied, measured ESE = 11 to 15 mR (Winstanley 1990a,b; Noonan 1991; Thomas 1991)
1993–present	Bennett: Stationary general-purpose radiographic system, Kodak M35A X-OMAT film processor, Lanex Regular screens, ESE = 12 mR (Thomas 1993) to 14 mR (Miles 1999); also 110 kVp, 200 mA, 0.017 s, ESE = 14 mR (LLNL 2004)

No information is known about the X-ray equipment used from 1952 to about 1970 and, therefore, the doses from this period come from the default values in ORAUT-OTIB-0006 (ORAUT 2005).

Graham and Williams (1975) describe results of an in-house radiation survey of the Fischer X-ray machine in the Medical Department by the LLNL Health Physics Group. Measurements resulted in an ESE of 19 mR [at a source-to-skin distance (SSD) of 157 cm], for a "typical" chest radiograph (100 kVp, 100 mA, 1/20 s), and filtration of 3.0 mm Al. This would result in an HVL of about 3.0 at 100 kVp (NCRP 1989). Beam collimation was "satisfactory," although the position of the light beam used for centering needed correction. The results of the survey indicated that the facility was operating properly and had adequate shielding. Another survey report found for the Fischer unit (Myers and Williams 1979) compares design features with those recommended by the National Council on Radiation Protection and Measurements and the State of California.

The Fischer system was replaced by a Xonics general-purpose radiographic machine sometime around mid-1980. Surveys of the Xonics machine were made in 1980 (Stephens 1980), 1985 (Shingleton 1985), 1989 (de Castro 1989), 1990 (Van Pelt 1990), and 1991 (Thomas 1991). The pertinent technical data from these surveys are that the measured ESE for a PA chest was as high as 45 mR for this period (Van Pelt 1990), the kVp used for PA chests was around 114 kVp (Thomas 1991), and the HVL for that period was likely to be about 4.0 mm Al equivalent for 110 kVp (Stephens 1980; de Castro 1989; NCRP 1989). Another document dated after the August 15, 1990, survey by Van Pelt but before LLNL had received the written results of that survey mentions an ESE of 60 mR for PA chests (Winstanley 1990a). However, this appears to be an initial estimate that was lowered to 45 mR once the raw data had been analyzed and the formal report written. Van Pelt attributed the relatively high ESE of 45 mR to the blue-light-emitting screens and the blue-light-sensitive film, and recommended that LLNL update the screen/film combination to a more sensitive green-light-emitting screen used in combination with green-light-sensitive film. LLNL acted on this recommendation, and made the switch to the more sensitive screens and film in 1991 (Noonan 1991). This change resulted in a reduction of the ESE for a PA chest from 45 mR to 12 mR (Thomas 1991). For dose reconstruction, an ESE of 45 mR is assumed for 1981 through 1990 and 15 mR for 1991 through 1992, when the machine was retired.

The Bennett X-ray machine was installed at LLNL in September 1992 (Higginson 1992), replacing the Xonics unit. The Bennett machine uses a high-frequency generator that produces a more constant voltage across the X-ray tube and more radiation output per unit mAs (LLNL 2004). The new system underwent a complete in-depth survey by the Food and Drug Administration (FDA) on October 27, 1992 (Thomas 1993). All items tested were within Federal specifications. The estimated ESE with automatic exposure control was reported as 12.15 mR for a PA chest. Values of ESE in the range of 12 to 14 mR were reported for the PA chest projection from surveys during this period and a measured HVL of 4 mm Al at 90 kVp (Miles 1999; LLNL 2004).

3.4 ORGAN DOSE EQUIVALENTS

Table 3-3 lists the resultant organ dose equivalents (except for skin) for the periods during which each X-ray system was in use. Table 3-4 provides skin dose guidance for various chest projections and periods. Tables 3-5 and 3-6 provide the dose equivalent to various areas of the skin for all periods and chest projections.

3.5 UNCERTAINTY

ORAUT-OTIB-0006 (ORAUT 2005) lists the major sources of uncertainty in X-ray output intensity and subsequent dose to the worker. The five sources of uncertainty are (1) X-ray beam measurement error (±2%); (2) variation in peak kilovoltage (±9%); (3) variation in X-ray beam current (±5%); (4) variation in exposure time (±25%); and (5) variation in SSD as a result of worker size (±10%). The 10% uncertainty in output intensity as a result of worker size was based on an inverse square correction of output intensity changes resulting from differences of standard chest thickness of ±7.5 cm.

Information on worker thickness is rarely available, even in the medical literature. However, at the Savannah River Site, entrance skin dose measurements were made on nine workers of varying chest thicknesses (builds) (Cooley 1967). While Cooley did not report the measured chest thicknesses for these nine workers, the entrance skin doses were reported and reflect the increases in exposure

Table 3-3. Organ dose equivalents (rem) for chest projections for all periods.

Organ	Projection	1952–1969[a]	1970–1980	1981–1990	1991–1992	1993–present
Thyroid	PA	3.48E-02	8.74E-04	3.51E-03	1.17E-03	1.09E-03
	LAT/OBL	6.85E-02	6.32E-03	1.85E-02	6.15E-03	5.74E-03
Eye/brain	PA	6.40E-03	8.74E-04	3.51E-03	1.17E-03	1.09E-03
	LAT/OBL	6.85E-02	6.32E-03	1.85E-02	6.15E-03	5.74E-03
Ovaries	PA	2.50E-02	3.42E-05	2.34E-04	7.80E-05	7.28E-05
	LAT/OBL	1.30E-02	4.28E-05	2.81E-04	9.38E-05	8.75E-05
Urinary/bladder	PA	2.50E-02	3.42E-05	2.34E-04	7.80E-05	7.28E-05
	LAT/OBL	1.30E-02	4.28E-05	2.81E-04	9.38E-05	8.75E-05
Colon/rectum	PA	2.50E-02	3.42E-05	2.34E-04	7.80E-05	7.28E-05
	LAT/OBL	1.30E-02	4.28E-05	2.81E-04	9.38E-05	8.75E-05
Testes	PA	5.00E-03	1.90E-07	4.50E-07	1.05E-07	1.40E-07
	LAT/OBL	2.50E-03	4.75E-06	1.13E-05	3.75E-06	3.50E-06
Lungs (male)	PA	8.38E-02	9.42E-03	2.83E-02	9.42E-03	8.79E-03
	LAT/OBL	9.65E-02	1.12E-02	3.52E-02	1.17E-02	1.10E-02
Lungs (female)	PA	9.02E-02	1.02E-02	3.03E-02	1.01E-02	9.44E-03
	LAT/OBL	1.10E-01	1.27E-02	3.95E-02	1.32E-02	1.23E-02
Thymus	PA	9.02E-02	1.02E-02	3.03E-02	1.01E-02	9.44E-03
	LAT/OBL	1.10E-01	1.27E-02	3.95E-02	1.32E-02	1.23E-02
Esophagus	PA	9.02E-02	1.02E-02	3.03E-02	1.01E-02	9.44E-03
	LAT/OBL	1.10E-01	1.27E-02	3.95E-02	1.32E-02	1.23E-02
Stomach	PA	9.02E-02	1.02E-02	3.03E-02	1.01E-02	9.44E-03
	LAT/OBL	1.10E-01	1.27E-02	3.95E-02	1.32E-02	1.23E-02
Bone surface	PA	9.02E-02	1.02E-02	3.03E-02	1.01E-02	9.44E-03
	LAT/OBL	1.10E-01	1.27E-02	3.95E-02	1.32E-02	1.23E-02
Liver/gall bladder/spleen	PA	9.02E-02	1.02E-02	3.03E-02	1.01E-02	9.44E-03
	LAT/OBL	1.10E-01	1.27E-02	3.95E-02	1.32E-02	1.23E-02
Remainder organs	PA	9.02E-02	1.02E-02	3.03E-02	1.01E-02	9.44E-03
	LAT/OBL	1.10E-01	1.27E-02	3.95E-02	1.32E-02	1.23E-02
Breast	PA	9.80E-03	1.31E-03	5.22E-03	1.74E-03	1.62E-03
	LAT/OBL	1.28E-01	1.36E-02	3.86E-02	1.29E-02	1.20E-02
Uterus	PA	2.50E-02	4.37E-05	2.34E-04	7.80E-05	7.28E-05
	LAT/OBL	1.30E-02	4.28E-05	2.36E-04	7.88E-05	7.35E-05
Bone marrow (male)	PA	1.84E-02	2.22E-03	8.01E-03	2.67E-03	2.49E-03
	LAT/OBL	1.85E-02	2.28E-03	8.55E-03	2.85E-03	2.66E-03
Bone marrow (female)	PA	1.72E-02	2.13E-03	7.74E-03	2.58E-03	2.41E-03
	LAT/OBL	1.45E-02	1.81E-03	6.64E-03	2.21E-03	2.07E-03
Entrance skin[b]	PA	2.70E-01	2.66E-02	6.30E-02	2.10E-02	1.96E-02
	LAT/OBL	6.75E-01	6.65E-02	1.58E-01	5.25E-02	4.90E-02

a. Doses before 1970 are based on values in ORAUT-OTIB-0006 (ORAUT 2005).

b. Entrance skin dose is determined by multiplying the entrance air kerma in air by the backscatter factors of 1.35 and 1.40 for HVL of 2.5 mm Al and 3.0 or 4.0 mm Al, respectively, from NCRP Report 102 (NRCP 1989, Table B-8). Skin doses for all areas of skin are provided in Tables 3-4 and 3-5.

Table 3-4. Skin dose guidance for various chest projections and periods.[a]

Area of skin	PA before 1970	LAT before 1970	RAO before 1970	PA after 1970	LAT after 1970	RAO after 1970
Right front shoulder	EXSD	ENSD	EXSD	EXSD	ENSD	EXSD
Right back shoulder	ENSD	ENSD	ENSD	ENSD	ENSD	ENSD
Left front shoulder	EXSD	EXSD	EXSD	EXSD	EXSD	EXSD
Left back shoulder	ENSD	EXSD	ENSD	ENSD	EXSD	ENSD
Right upper arm to elbow	ENSD	ENSD	ENSD	10% ENSD	ENSD	10% ENSD
Left upper arm to elbow	ENSD	EXSD	ENSD	10% ENSD	EXSD	10% ENSD
Left hand	ENSD	10% ENSD	10% ENSD	10% ENSD	10% ENSD	10% ENSD
Right hand	ENSD	10% ENSD	10% ENSD	10% ENSD	10% ENSD	10% ENSD
Left elbow, forearm, wrist	ENSD	10% ENSD	10% ENSD	10% ENSD	10% ENSD	10% ENSD
Right elbow, forearm, wrist	ENSD	10% ENSD	10% ENSD	10% ENSD	10% ENSD	10% ENSD
Right side of head (including ear and temple)	10% ENSD	Eye/brain	10% EXSD	10% ENSD	10% ENSD	10% EXSD
Left side of head (including ear and temple)	10% ENSD	Eye/brain	10% ENSD	10% ENSD	10% ENSD	10% ENSD
Front left thigh	RSD (0.52 m)	RSD (0.52 m)	RSD (0.52 m)	RSD (0.52 m)	RSD (0.52 m)	RSD (0.52 m)
Back left thigh	RSD (0.52 m)	RSD (0.52 m)	RSD (0.52 m)	RSD (0.52 m)	RSD (0.52 m)	RSD (0.52 m)
Front right thigh	RSD (0.52 m)	RSD (0.52 m)	RSD (0.52 m)	RSD (0.52 m)	RSD (0.52 m)	RSD (0.52 m)
Back right thigh	RSD (0.52 m)	RSD (0.52 m)	RSD (0.52 m)	RSD (0.52 m)	RSD (0.52 m)	RSD (0.52 m)
Left knee and below	RSD (0.86 m)	RSD (0.86 m)	RSD (0.86 m)	RSD (0.86 m)	RSD (0.86 m)	RSD (0.86 m)
Right knee and below	RSD (0.86 m)	RSD (0.86 m)	RSD (0.86 m)	RSD (0.86 m)	RSD (0.86 m)	RSD (0.86 m)
Left side of face	Eye/brain	Eye/brain	ENSD	Eye/brain	10% ENSD	10% ENSD
Right side of face	Eye/brain	Eye/brain	EXSD	Eye/brain	10% ENSD	10% EXSD
Left side of neck	ENSD	Eye/brain	ENSD	10% ENSD	10% ENSD	10% ENSD
Right side of neck	ENSD	Eye/brain	EXSD	10% ENSD	10% ENSD	10% EXSD
Back of head	10% ENSD	Eye/brain	10% ENSD	10% ENSD	10% ENSD	10% ENSD
Front of neck	Eye/brain	Eye/brain	Eye/brain	Thyroid	10% ENSD	Thyroid
Back of neck	ENSD	Eye/brain	ENSD	10% ENSD	10% ENSD	10% ENSD
Front torso: base of neck to end of sternum	EXSD	Lung	EXSD	EXSD	Lung	EXSD
Front torso: end of sternum to lowest rib	EXSD	Lung	EXSD	EXSD	Lung	EXSD
Front torso: lowest rib to iliac crest	EXSD	Lung	EXSD	10% EXSD	10% lung	10% EXSD
Front torso: iliac crest to pubis	10% EXSD	10% lung	10% EXSD	10% EXSD	10% lung	10% EXSD
Back torso: base of neck to mid-back	ENSD	Lung	ENSD	ENSD	Lung	ENSD
Back torso: mid-back to lowest rib	ENSD	Lung	ENSD	ENSD	Lung	ENSD
Back torso: lowest rib to iliac crest	ENSD	Lung	ENSD	10% ENSD	10% lung	10% ENSD
Back torso: buttocks (Iliac crest and below)	10% ENSD	10% lung	10% ENSD	10% ENSD	10% lung	10% ENSD
Right torso: base of neck to end of sternum	ENSD	ENSD	EXSD	ENSD	ENSD	EXSD
Right torso: end of sternum to lowest rib	ENSD	ENSD	EXSD	ENSD	ENSD	EXSD
Right torso: lowest rib to iliac crest	ENSD	ENSD	EXSD	10% ENSD	10% ENSD	10% EXSD
Right torso: iliac crest to pubis (right hip)	10% ENSD	10% ENSD	10% EXSD	10% ENSD	10% ENSD	10% EXSD
Left torso: base of neck to end of sternum	ENSD	EXSD	ENSD	ENSD	EXSD	ENSD

Area of skin	PA before 1970	LAT before 1970	RAO before 1970	PA after 1970	LAT after 1970	RAO after 1970
Left torso: end of sternum to lowest rib	ENSD	EXSD	ENSD	ENSD	EXSD	ENSD
Left torso: lowest rib to iliac crest	ENSD	EXSD	ENSD	10% ENSD	10% EXSD	10% ENSD
Left torso: iliac crest to pubis (left hip)	10% ENSD	10% EXSD	10% ENSD	10% ENSD	10% EXSD	10% ENSD

a. The general method for calculating skin doses is presented in ORAUT-OTIB-0006, Appendix A. (ORAUT 2005)

Table 3-5. Skin dose (rem) from various chest projections, 1952–1990.[a]

Area of skin	PA 1952–1969	LAT 1952–1969	RAO 1952–1969	PA 1970–1980	LAT 1970–1980	RAO 1970–1980	PA 1981–1990	LAT 1981–1990	RAO 1981–1990
Right front shoulder	5.9E-03	6.75E-01	3.0E-03	7.E-04	6.65E-02	3.E-04	2.1E-03	1.58E-01	1.2E-03
Right back shoulder	2.70E-01	6.75E-01	6.75E-01	2.66E-02	6.65E-02	6.65E-02	6.30E-02	1.58E-01	1.58E-01
Left front shoulder	5.9E-03	3.0E-03	3.0E-03	7.E-04	3.E-04	3.E-04	2.1E-03	1.2E-03	1.2E-03
Left back shoulder	2.70E-01	3.0E-03	6.75E-01	2.66E-02	3.E-04	6.65E-02	6.30E-02	1.2E-03	1.58E-01
Right upper arm to elbow	2.70E-01	6.75E-01	6.75E-01	2.7E-03	6.65E-02	6.7E-03	6.3E-03	1.58E-01	1.58E-02
Left upper arm to elbow	2.70E-01	3.0E-03	6.75E-01	2.7E-03	3.E-04	6.7E-03	6.3E-03	1.2E-03	1.58E-02
Left hand	2.70E-01	6.75E-02	6.75E-02	2.7E-03	6.7E-03	6.7E-03	6.3E-03	1.58E-02	1.58E-02
Right hand	2.70E-01	6.75E-02	6.75E-02	2.7E-03	6.7E-03	6.7E-03	6.3E-03	1.58E-02	1.58E-02
Left elbow, forearm, wrist	2.70E-01	6.75E-02	6.75E-02	2.7E-03	6.7E-03	6.7E-03	6.3E-03	1.58E-02	1.58E-02
Right elbow, forearm, wrist	2.70E-01	6.75E-02	6.75E-02	2.7E-03	6.7E-03	6.7E-03	6.3E-03	1.58E-02	1.58E-02
Right side of head including ear and temple	2.70E-02	6.85E-02	3.E-04	2.7E-03	6.7E-03	3.E-05	6.3E-03	1.58E-02	1.E-04
Left side of head including ear and temple	2.70E-02	6.85E-02	6.75E-02	2.7E-03	6.7E-03	6.7E-03	6.3E-03	1.58E-02	1.58E-02
Front left thigh	8.E-05	1.E-04	1.E-04	9.E-06	1.E-05	1.E-05	2.E-05	3.E-05	3.E-05
Back left thigh	8.E-05	1.E-04	1.E-04	9.E-06	1.E-05	1.E-05	2.E-05	3.E-05	3.E-05
Front right thigh	8.E-05	1.E-04	1.E-04	9.E-06	1.E-05	1.E-05	2.E-05	3.E-05	3.E-05
Back right thigh	8.E-05	1.E-04	1.E-04	9.E-06	1.E-05	1.E-05	2.E-05	3.E-05	3.E-05
Left knee and below	3.E-05	4.E-05	4.E-05	3.E-06	4.E-06	4.E-06	9.E-06	1.E-05	1.E-05
Right knee and below	3.E-05	4.E-05	4.E-05	3.E-06	4.E-06	4.E-06	9.E-06	1.E-05	1.E-05
Left side of face	6.4E-03	6.85E-02	6.75E-01	9.E-04	6.7E-03	6.7E-03	3.5E-03	1.58E-02	1.58E-02
Right side of face	6.4E-03	6.85E-02	3.0E-03	9.E-04	6.7E-03	3.E-05	3.5E-03	1.58E-02	1.E-04
Left side of neck	2.70E-01	6.85E-02	6.75E-01	2.7E-03	6.7E-03	6.7E-03	6.3E-03	1.58E-02	1.58E-02
Right side of neck	2.70E-01	6.85E-02	3.0E-03	2.7E-03	6.7E-03	3.E-05	6.3E-03	1.58E-02	1.E-04
Back of head	2.70E-02	6.85E-02	6.75E-02	2.7E-03	6.7E-03	6.7E-03	6.3E-03	1.58E-02	1.58E-02
Front of neck	6.4E-03	6.85E-02	6.85E-02	9.E-04	6.7E-03	6.3E-03	3.5E-03	1.58E-02	1.85E-02
Back of neck	2.70E-01	6.85E-02	6.75E-01	2.7E-03	6.7E-03	6.7E-03	6.3E-03	1.58E-02	1.58E-02
Front torso: base of neck to end of sternum	5.9E-03	1.10E-01[b]	3.0E-03	7.E-04	1.27E-02[b]	3.E-04	2.1E-03	3.95E-02[b]	1.2E-03
Front torso: end of sternum to lowest rib	5.9E-03	1.10E-01[b]	3.0E-03	7.E-04	1.27E-02[b]	3.E-04	2.1E-03	3.95E-02[b]	1.2E-03
Front torso: lowest rib to iliac crest	5.9E-03	1.10E-01[b]	3.0E-03	7.E-05	1.3E-03[b]	3.E-05	2.E-04	3.9E-03[b]	1.E-04

Area of skin	PA 1952–1969	LAT 1952–1969	RAO 1952–1969	PA 1970–1980	LAT 1970–1980	RAO 1970–1980	PA 1981–1990	LAT 1981–1990	RAO 1981–1990
Front torso: iliac crest to pubis	6.E-04	1.10E-02[b]	3.E-04	7.E-05	1.3E-03[b]	3.E-05	2.E-04	3.9E-03[b]	1.E-04
Back torso: base of neck to mid-back	2.70E-01	1.10E-01[b]	6.75E-01	2.66E-02	1.27E-02[b]	6.65E-02	6.30E-02	3.95E-02[b]	1.58E-01
Back torso: mid-back to lowest rib	2.70E-01	1.10E-01[b]	6.75E-01	2.66E-02	1.27E-02[b]	6.65E-02	6.30E-02	3.95E-02[b]	1.58E-01
Back torso: lowest rib to iliac crest	2.70E-01	1.10E-01[b]	6.75E-01	2.7E-03	1.3E-03[b]	6.7E-03	6.3E-03	3.9E-03[b]	1.58E-02
Back torso: buttocks (Iliac crest and below)	2.70E-02	1.10E-02[b]	6.75E-02	2.7E-03	1.3E-03[b]	6.7E-03	6.3E-03	3.9E-03[b]	1.58E-02
Right torso: base of neck to end of sternum	2.70E-01	6.75E-01	3.0E-03	2.66E-02	6.65E-02	3.E-04	6.30E-02	1.58E-01	1.2E-03
Right torso: end of sternum to lowest rib	2.70E-01	6.75E-01	3.0E-03	2.66E-02	6.65E-02	3.E-04	6.30E-02	1.58E-01	1.2E-03
Right torso: lowest rib to iliac crest	2.70E-01	6.75E-01	3.0E-03	2.7E-03	6.7E-03	3.E-05	6.3E-03	1.58E-02	1.E-04
Right torso: iliac crest to pubis (right hip)	2.70E-02	6.75E-02	3.E-04	2.7E-03	6.7E-03	3.E-05	6.3E-03	1.58E-02	1.E-04
Left torso: base of neck to end of sternum	2.70E-01	3.0E-03	6.75E-01	2.66E-02	3.E-04	6.65E-02	6.30E-02	1.2E-03	1.58E-01
Left torso: end of sternum to lowest rib	2.70E-01	3.0E-03	6.75E-01	2.66E-02	3.E-04	6.65E-02	6.30E-02	1.2E-03	1.58E-01
Left torso: lowest rib to iliac crest	2.70E-01	3.0E-03	6.75E-01	2.7E-03	3.E-05	6.7E-03	6.3E-03	1.E-04	1.58E-02
Left torso: iliac crest to pubis (left hip)	2.70E-02	3.E-04	6.75E-02	2.7E-03	3.E-05	6.7E-03	6.3E-03	1.E-04	1.58E-02

a. Values less than 1 mrem shown to one significant digit.
b. Based on value for female lung.

Table 3-6. Skin dose (rem) from various chest projections, 1991–present.[a]

Area of skin	PA 1991–1992	LAT 1991–1992	RAO 1991–1992	PA 1993 –present	LAT 1993–present	RAO 1993–present
Right front shoulder	7.E-04	5.25E-02	4.E-04	7.E-04	4.90E-02	4.E-04
Right back shoulder	2.10E-02	5.25E-02	5.25E-02	1.96E-02	4.90E-02	4.90E-02
Left front shoulder	7.E-04	4.E-04	4.E-04	7.E-04	4.E-04	4.E-04
Left back shoulder	2.10E-02	4.E-04	5.25E-02	1.96E-02	4.E-04	4.90E-02
Right upper arm to elbow	2.1E-03	5.25E-02	5.3E-03	2.0E-03	4.90E-02	4.9E-03
Left upper arm to elbow	2.1E-03	4.E-04	5.3E-03	2.0E-03	4.E-04	4.9E-03
Left hand	2.1E-03	5.3E-03	5.3E-03	2.0E-03	4.9E-03	4.9E-03
Right hand	2.1E-03	5.3E-03	5.3E-03	2.0E-03	4.9E-03	4.9E-03
Left elbow, forearm, wrist	2.1E-03	5.3E-03	5.3E-03	2.0E-03	4.9E-03	4.9E-03
Right elbow, forearm, wrist	2.1E-03	5.3E-03	5.3E-03	2.0E-03	4.9E-03	4.9E-03
Right side of head including ear and temple	2.1E-03	5.3E-03	4.E-05	2.0E-03	4.9E-03	4.E-05
Left side of head including ear and temple	2.1E-03	5.3E-03	5.3E-03	2.0E-03	4.9E-03	4.9E-03
Front left thigh	8.E-06	1.E-05	1.E-05	8.E-06	1.E-05	1.E-05
Back left thigh	8.E-06	1.E-05	1.E-05	8.E-06	1.E-05	1.E-05
Front right thigh	8.E-06	1.E-05	1.E-05	8.E-06	1.E-05	1.E-05
Back right thigh	8.E-06	1.E-05	1.E-05	8.E-06	1.E-05	1.E-05
Left knee and below	3.E-06	4.E-06	4.E-06	3.E-06	4.E-06	4.E-06
Right knee and below	3.E-06	4.E-06	4.E-06	3.E-06	4.E-06	4.E-06
Left side of face	1.2E-03	5.3E-03	5.3E-03	1.1E-03	4.9E-03	4.9E-03
Right side of face	1.2E-03	5.3E-03	4.E-05	1.1E-03	4.9E-03	4.E-05
Left side of neck	2.1E-03	5.3E-03	5.3E-03	2.0E-03	4.9E-03	4.9E-03
Right side of neck	2.1E-03	5.3E-03	4.E-05	2.0E-03	4.9E-03	4.E-05
Back of head	2.1E-03	5.3E-03	5.3E-03	2.0E-03	4.9E-03	4.9E-03
Front of neck	1.2E-03	5.3E-03	6.2E-03	1.1E-03	4.9E-03	5.7E-03
Back of neck	2.1E-03	5.3E-03	5.3E-03	2.0E-03	4.9E-03	4.9E-03
Front torso: base of neck to end of sternum	7.E-04	1.32E-02	4.E-04	7.E-04	1.23E-02	4.E-04
Front torso: end of sternum to lowest rib	7.E-04	1.32E-02	4.E-04	7.E-04	1.23E-02	4.E-04
Front torso: lowest rib to iliac crest	7.E-05	1.3E-03	4.E-05	7.E-05	1.2E-03	4.E-05
Front torso: iliac crest to pubis	7.E-05	1.3E-03	4.E-05	7.E-05	1.2E-03	4.E-05
Back torso: base of neck to mid-back	2.10E-02	1.32E-02	5.25E-02	1.96E-02	1.23E-02	4.90E-02
Back torso: mid-back to lowest rib	2.10E-02	1.32E-02	5.25E-02	1.96E-02	1.23E-02	4.90E-02
Back torso: lowest rib to iliac crest	2.1E-03	1.3E-03	5.3E-03	2.0E-03	1.2E-03	4.9E-03
Back torso: buttocks (Iliac crest and below)	2.1E-03	1.3E-03	5.3E-03	2.0E-03	1.2E-03	4.9E-03
Right torso: base of neck to end of sternum	2.10E-02	5.25E-02	4.E-04	1.96E-02	4.90E-02	4.E-04
Right torso: end of sternum to lowest rib	2.10E-02	5.25E-02	4.E-04	1.96E-02	4.90E-02	4.E-04
Right torso: lowest rib to iliac crest	2.1E-03	5.3E-03	4.E-05	2.0E-03	4.9E-03	4.E-05
Right torso: iliac crest to pubis (right hip)	2.1E-03	5.3E-03	4.E-05	2.0E-03	4.9E-03	4.E-05

Area of skin	PA 1991–1992	LAT 1991–1992	RAO 1991–1992	PA 1993 –present	LAT 1993–present	RAO 1993–present
Left torso: base of neck to end of sternum	2.10E-02	4.E-04	5.25E-02	1.96E-02	4.E-04	4.90E-02
Left torso: end of sternum to lowest rib	2.10E-02	4.E-04	5.25E-02	1.96E-02	4.E-04	4.90E-02
Left torso: lowest rib to iliac crest	2.1E-03	4.E-05	5.3E-03	2.0E-03	4.E-05	4.9E-03
Left torso: iliac crest to pubis (Left hip)	2.1E-03	4.E-05	5.3E-03	2.0E-03	4.E-05	4.9E-03

a. Values less than 1 mrem shown to one significant digit.

needed to radiograph thicker body parts, in this case chests. Cooley reported the mean of the measured entrance skin doses as 27 mrem. The standard uncertainty of the range of measurements is 5.6, resulting in an uncertainty of 21% from this source.

Substituting this value into the calculation for combined uncertainty described in ORAUT-OTIB-0006 (ORAUT 2005) rather than the 10% value used in that document, the resultant standard uncertainty is 34% from these five sources. Rounding this up to 35% would seem to provide an adequate and suitably conservative indication of uncertainty.

3.6 ATTRIBUTIONS AND ANNOTATIONS

Where appropriate in this document, bracketed callouts have been inserted to indicate information, conclusions, and recommendations provided to assist in the process of worker dose reconstruction. These callouts are listed here in the Attributions and Annotations section, with information to identify the source and justification for each associated item. Conventional References, which are provided in the next section of this document, link data, quotations, and other information to documents available for review on the Project's Site Research Database (SRDB).

[1] Thomas, Elyse M. ORAU Team. Principal Medical Dosimetrist. April 2010.
Analysis of a random sample of claim file records from LLNL.

[2] Thomas, Elyse M. ORAU Team. Principal Medical Dosimetrist. April 2010.
Analysis of a random sample of claim file records from LLNL.

[3] Thomas, Elyse M. ORAU Team. Principal Medical Dosimetrist. April 2010.
Analysis of a random sample of claim file records from LLNL.

[4] Thomas, Elyse M. ORAU Team. Principal Medical Dosimetrist. April 2010.
Analysis of a random sample of claim file records from LLNL. Radiation from X-rays received in the diagnosis of injuries or illnesses or for therapeutic reasons is excluded from radiation dose reconstruction under EEOICPA.

[5] Thomas, Elyse M. ORAU Team. Principal Medical Dosimetrist. April 2010.
Analysis of a random sample of claim file records from LLNL.

[6] Thomas, Elyse M. ORAU Team. Principal Medical Dosimetrist. April 2010.
Dr. James Turner, author of this TBD reviewed the archived X-ray portfolios of seven randomly selected individuals who were employed at LLNL in the 1950s and 1960s. No small-format films were found.

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GLOSSARY

absorbed dose
Amount of energy (ergs or joules) deposited in a substance by ionizing radiation per unit mass (grams or kilograms) of the substance and measured in units of rads or grays.

ampere (A)
International System unit of electrical current equal to 1 coulomb per second.

backscatter
Reflection or refraction of radiation at angles over 90 degrees from its original direction.

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

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

entrance air kerma in air
The sum of kinetic energy of all charge particles liberated per unit mass of air at the point where an X-ray beam enters the skin surface (without backscatter). The unit is the joule per kilogram ($J\ kg^{-1}$) and is given the special name gray (Gy).

entrance skin exposure (ESE)
Exposure in air, measured in units of roentgens, at the point where an X-ray beam enters the skin surface (without backscatter).

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

gray (Gy)
International System unit of absorbed radiation dose, which is the amount of energy from any type of ionizing radiation deposited in any medium; 1 Gy equals 1 joule per kilogram or 100 rads.

half-value layer (HVL)
Thickness of a specified substance, usually specified in equivalent millimeters of aluminum, that filters an X-ray beam to reduce the kerma rate by one-half. See *filtration*.

kerma
Measure in units of absorbed dose (usually grays but sometimes rads) of the energy released by radiation from a given amount of a substance. Kerma is the sum of the initial kinetic energies of all the charged ionizing particles liberated by uncharged ionizing particles (neutrons and photons) per unit mass of a specified material. Free-in-air kerma refers to the amount of radiation at a location before adjustment for any external shielding from structures or terrain. The word derives from kinetic energy released per unit mass.

lateral (LAT, lat)
Orientation of the body during an X-ray procedure in which the X-rays pass from one side of the body to the other.

lordotic
Projection radiograph of the chest used to diagnose conditions affecting the chest, its contents, and nearby structures.

milliampere-second (mAs)
In relation to radiography, product of the average X-ray beam current in milliamperes and the time of the exposure in seconds. These factors are selectable on the control panel of most medical X-ray equipment.

occupational medical dose
Dose from X-ray procedures performed for medical screening of workers as part of an occupational health program. Doses from X-rays used to diagnose diseases or injuries, even if incurred on the job, are not considered occupational and are therefore not eligible to be included in dose reconstruction under EEOICPA.

photofluorography (PFG)
Historical radiographic technique used for chest images for screening a large number of people in a short period of time. The X-ray image produced on a fluorescent screen was photographed on 4- by 5-inch film. PFG was the primary method of screening large populations for tuberculosis before the advent of nonradiographic screening methods. Also called fluorography or mass miniature radiography. Not to be confused with *fluoroscopy*.

posterior-anterior (PA)
Physical orientation of the body relative to a penetrating directional radiation field such that the radiation passes through the body from the back to the front.

preemployment X-ray
An X-ray, usually of the chest, taken before hire or assignment to a specific job. The purpose of preemployment X-rays was to screen for active disease, such as tuberculosis.

primary X-rays
X-rays that emerge from the exit port of an X-ray tube and through the tube housing and/or collimator. Also called primary beam or useful beam.

probability of causation (POC)
For purposes of dose reconstruction for the Energy Employees Occupational Illness Compensation Program Act, the percent likelihood, at the 99th percentile, that a worker incurred a particular cancer from occupational exposure to radiation.

projection
Description of the path of an X-ray beam from the X-ray tube to the image receptor. For example, posterior-anterior and lateral are two common projections in chest radiography.

rad
Traditional unit for expressing absorbed radiation dose, which is the amount of energy from any type of ionizing radiation deposited in any medium. A dose of 1 rad is equivalent to the absorption of 100 ergs per gram (0.01 joules per kilogram) of absorbing tissue. The rad has been replaced by the gray in the International System of Units (100 rads = 1 gray). The word derives from <u>r</u>adiation <u>a</u>bsorbed <u>d</u>ose.

radiograph

Static images produced on radiographic film by gamma rays or X-rays after passing through matter. In the context of EEOICPA, radiographs are X-ray images of the various parts of the body used to screen for disease. See *radiology*.

radiography

The process of producing images on film (or other media) with radiation.

radiology

Science of using X-rays to produce images on photographic film, especially for medical purposes, as well as of interpreting those images.

rem

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

roentgen

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

source-to-skin distance (SSD)

Distance from the X-ray machine target (anode) to the skin of the person being X-rayed. This distance varies with the size of the person being radiographed.

X-ray

(1) See *X-ray radiation*. (2) See *radiograph*.

X-ray radiation

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