ORAU TEAM
Dose Reconstruction
Project for NIOSH

Oak Ridge Associated Universities I Dade Moeller I MJW Technical Services

DOE Review Release 01/13/2014

Document Title:	Document Number:	ORAUT-TKBS-0017-3
Fernald Environmental Management Project – Occupational Medical Dose	Revision:	01
	Effective Date:	01/02/2014
	Type of Document:	TBD
	Supersedes:	Revision 00

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Approval:	Signature on File David S. Sundin, Deputy Director, DCAS	Approval Date:	01/02/2014

☐ New ☒ Total Rewrite ☐ Revision ☐ Page Change

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PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
02/11/2004	00	New Technical Basis Document for the Fernald Environmental Management Project – Occupational Medical Dose. Incorporates formal internal and NIOSH review comments. First approved issue. Initiated by Terry A. Kuykendall.
01/02/2014	01	Revision to correct errors in dose from LAT chest X-rays. Skin doses were added for all projections and periods. Dose to B-lymphocytes added. Incorporates formal internal and NIOSH review comments. Constitutes a total rewrite of the document. Training required: As determined by the Objective Manager. Initiated by Karen S. Kent.

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ACRONYMS AND ABBREVIATIONS

CFR	*Code of Federal Regulations*
cGy	centigray
cm	centimeter
DCF	dose conversion factor
DOE	U.S. Department of Energy
DOL	U.S. Department of Labor
EEOICPA	Energy Employees Occupational Illness Compensation Program Act of 2000
ENSD	entrance skin dose
eq	equivalent
ESE	entrance skin exposure
EXSD	exit skin dose
FDA	Food and Drug Administration
FEMP	Fernald Environmental Management Project
FMPC	Feed Materials Production Center
GE	General Electric Company
Gy	gray
HVL	half-value layer
ICRP	International Commission on Radiological Protection
in.	inch
IREP	Interactive RadioEpidemiological Program
keV	kiloelectron-volt (1,000 electron-volts)
kVp	peak kilovoltage
LAT	lateral
mA	milliampere
mAs	milliampere-second
mm	millimeter
mR	milliroentgen
mrem	millirem
NCRP	National Council on Radiation Protection and Measurements
NIOSH	National Institute for Occupational Safety and Health
OBL	oblique
ORAU	Oak Ridge Associated Universities
PA	posterior-anterior
PFG	photofluorography
POC	probability of causation
R	roentgen
RAO	right anterior oblique
RSD	remote skin dose

SEC	Special Exposure Cohort
SRDB Ref ID	Site Research Database Reference Identification (number)
U.S.C.	United States Code
§	section or sections

3.1 INTRODUCTION

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

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

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

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

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

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

3.1.1 Purpose

The purpose of this document is to provide a technical basis for the occupational medical dose for energy employees who were employed at Fernald Environmental Management Project (FEMP)

3.1.2 Scope

This document contains the technical data necessary to estimate the radiation dose to organs from medical X-ray procedures that workers received at FEMP, formerly known as the Feed Materials Production Center (FMPC). Under the requirements of EEOICPA, only the dose from medical X-rays received for screening and as a condition of employment is eligible to be included in dose reconstruction.

Occupational medical X-ray dose is a function of many variables including number and type of radiographic examinations, the projection(s) performed, degree of collimation or beam restriction, type of equipment and technique factors used. Section 3.2 discusses examination frequencies, and Section 3.3 describes the equipment and techniques FEMP used. Section 3.4 describes organ dose calculations and provides the results, and Section 3.5 discusses uncertainty in the results.

3.2 EXAMINATION FREQUENCIES

Fernald required preemployment, annual, and termination physical examinations as part of its occupational health and safety program. These medical examinations typically included chest X-rays (Quigley 1951). A review of the claim file records and historical documentation indicated that the most common X-ray screening examination was the posterior-anterior (PA) chest projection. The lateral (LAT) and right anterior oblique (RAO) chest appears on occasion, and was likely performed at the physician’s request. Both of these projections were useful for asbestos workers in evaluating asbestosis, an occupational disease. Therefore, the dose from these projections should be included in dose reconstruction. There is no evidence in the claim file records that photofluorography (PFG) was performed on any workers, nor is there historical evidence of PFG equipment at Fernald.

The frequency of medical X-rays varied over the years of Fernald operation. Table 3-1 shows the frequency of chest X-ray screening for different age groups over the years of operation. The dose reconstructor should use the X-rays listed in the claim file records for dose reconstruction whenever those records are provided. The frequency listed in Table 3-1 can be used when records have not been provided.

Table 3-1. Frequency of occupational chest X-rays at Fernald.

Period	Frequency	Projection(s)	Employees
1952–1981	Pre-employment	PA chest	All employees[a]
	Annual	PA chest	All employees[b]
	Termination	PA chest	All employees[b]
1981–1987	Pre-employment l	PA chest	All employees
	Annual	PA chest	Employees over 45 years old[c]
	Every 2 years	PA chest	Employees under 45 years old[c]
1988-2006	Pre-employment l	PA chest, LAT discretionary	All employees[d]
	Annual (offered)	PA chest, LAT discretionary	All employees[d]

a. Quigley (1951, p. 10).
b. Schoen and Heacker (1961, p. 4).
c. Rardin (1983, p. 12).
d. Jacoboski (1987, pp. 26–27).

The claim file records indicate the purpose of the X-ray examinations as “annual,” “pre,” for preemployment, “term” for termination, or “dispensary” for examinations requested as a result of individual worker symptoms or injuries. For example, lumbar spine radiographs appear in some of the claim file records, but the reason indicated on the requisition is most often “dispensary,” which suggests that the lumbar spine radiographs were performed for individual back pain or injury but not for routine screening on asymptomatic workers. The dose from lumbar spine procedures (or any others for that matter) should not be included in dose reconstruction when the requisition states “dispensary” as a justification for the examination.

Many of the claim file records contain the X-ray requisition as well as the radiologists’ interpretation or report. The dates on these documents may be separated by a few days to a week, but may also contain the date the examination was actually performed. The dose reconstructor should look carefully at the dates on these documents to ensure that the number of X-ray procedures in dose reconstruction is accurate for each worker. It is possible that some of the X-ray examinations were performed off the FEMP site at local area hospitals, but there does not seem to be a fixed pattern, and no clear evidence exists in relation to when or for whom this might have occurred. If dose reconstructors are certain that X-rays were performed off-site, then dose from these procedures should not be included in dose reconstruction (ORAUT 2011b). Otherwise, dose reconstructors should assume that all X-ray procedures were performed on the Fernald site from 1952 to 2006, when buildings at Fernald were demolished and the X-ray equipment in them was removed from the site.

3.3 EQUIPMENT AND TECHNIQUES

What is known about the medical X-ray equipment Fernald used is summarized in Table 3-2 below, and each type and period of use is discussed in the following subsections.

Table 3-2. Description of Fernald medical X-ray equipment.

Period	Equipment	Technique Factors
1952–1973	Keleket X-ray unit, 2.5-mm Al eq total filtration	Technique factors are unknown, but exposure in air measurements exist.[a]
1974–1987	Bennett X-Ray Corporation Model 300	6.7 mAs at 74 kVp for PA chest projections, with 2.5 mm Al eq total filtration,[b,c] 6.7 mAs at 86 kvp,[d] and 6.7 mAs at 90 kVp[e] for PA chest projections.
1988–1993	GE Model 46-2611-85G1, Lanex Regular screens/film	100 kVp, 200 mA, 0.025 s[f].
1994–2006	GE Model 46-2611-85G1, plus Kodak InSight Thoracic Imaging System	110kVp 8 mAs,[g] and 126 kVp 6.4 mAs[h]; HVL 3.5 mm Al at 120 kVp[h].

a. Fischoff (1961, pp. 6-8).
b. Boback (1977, pp. 9-10).
c. Scudder (1974, p. 1).
d. Hinnefeld (1984, p.18).
e. Jacoboski (1987, p. 32).
f. Kodak (1988, p. 35).
g. Bolen (1995, p. 68).
h. Bolen (2000, p. 41).

3.3.1 Keleket X-Ray Machine, 1952 to 1973

Medical X-ray equipment was first installed at Fernald in 1952 (Blatz 1952). The make and model of the equipment is not known, and the technique factors are not available.

The earliest information about actual X-ray equipment at Fernald is a survey in 1961 on a Keleket machine (Fischoff 1961). The purpose of the survey was to measure the exposure in air and on standard film badges for typical X-ray settings on the machine such as would be used to X-ray workers to determine the response of the film badge. Then, if a worker accidentally wore his badge during a medical X-ray examination, the film badge density could be corrected to the true occupational exposure with the calibration curves resulting from the survey results. Only two survey measurements (out of 15) were made at 72 in., the typical distance for chest X-rays. The two measurements at 72 in. were made at 90 kVp, at 50 and 150 mAs. Given the purpose of the survey, it was assumed these were the techniques for the PA and LAT chest, respectively, on this machine at this time.

The two measurements described above show exposure in air results of 0.10 and 0.30 R for the 50- and 150-mAs exposures at 90 kVp and 72 in. The survey states that the Keleket machine had 2.5 mm Al eq total filtration. Using these data and the information and equations in ORAUT-OTIB-0006, *Dose Reconstruction from Occupational Medical X-Ray Procedures* (ORAUT 2011a), the resulting incident air kerma values (at 155 cm) for the PA and LAT chest X-rays are 0.122 and 0.367 cGy, respectively. The half-value layer (HVL) at 90 kVp for 2.5 mm Al eq total filtration is 2.6 mm Al, which was rounded to 2.5 mm Al for selection of dose conversion factors (DCFs) for dose reconstruction.

It is possible that the Keleket X-ray machine that was surveyed in 1961 was the original X-ray machine, which was installed at Fernald in 1952. However, this is not known for certain from the currently available information. Because it is possible, the organ doses that are calculated based on the measurements on the Keleket machine are assumed to be those from the start of X-rays at Fernald in 1952.

3.3.2 Bennett Equipment, 1974 to 1987

The manufacturer of the medical X-ray equipment that was used during this period is not clear, but several usable sources of technical information exist about the equipment. Survey measurements on the equipment are documented for 1977 (Boback 1977). The purposes of this survey were to measure the entrance skin exposures (ESE) for various X-ray examinations and to compare them to published national Entrance Skin Exposure Guides. The results show that the measured ESE on the Fernald equipment was 11.4 mR for chest technique factors of 74 kVp and 6.7 mAs. The data also specify that this measurement was for a 23-cm chest with a 72-in. source-to-image distance on a machine that had 2.5 mm Al equivalent (eq) total filtration. The HVL for 2.5 mm Al eq total filtration at 74 kVp is 2.3 mm Al, which was rounded to an HVL of 2.5. This ESE result is reproducible using the data and cited reference. The ESE of 11.4 mR is equal to 0.01 cGy after converting the ESE to incident air kerma using the equations in ORAUT-OTIB-0006 (ORAUT 2011a).

Another survey in 1974 to evaluate scatter around the X-ray room does not contain much information but indicates that the scatter measurements were performed at 6.7 mAs (Scudder 1974). It is likely that this refers to technique factors for a PA chest because the numbers correspond to the technique factors for the PA chest in Boback (1977). Therefore, the same organ dose values were used beginning in 1974.

The first concrete mention of the Bennett X-ray machine is in a survey of the X-ray equipment in 1984 (Hinnefeld 1984, p. 16). This document describes survey procedures that would have been used on equipment that was manufactured after about 1974. However, no other technical details are provided.

Technique factors in another procedure document from 1987 indicate that the technique factors for a large male were approximately 90 kVp, 100 mA, and 1/15 second (or 6.7 mAs) (Jacoboski 1987, p. 32). Using average air kerma rates for single-phase X-ray equipment in National Council on Radiation Protection and Measurements (NCRP) Report 102 (NCRP 1997, Table B-3) and correcting to a source-to-skin distance of 155 cm, these technique factors result in an incident air kerma of 0.017 cGy for the PA chest.

It is reasonable to conclude after reviewing these various sources of technical information that the X-ray machine FEMP used from 1974 to 1987 was probably the Bennett X-ray machine. The various survey results and technique factors all lead to similar incident air kerma results and HVLs. Organ doses for this period were based on the technique factors for a large male resulting in an incident air kerma of 0.017 cGy for the PA chest and 0.0425 cGy for the LAT chest (Jacoboski 1987, p. 32). The HVL for 90 kVp assuming 2.5 mm Al eq total filtration is 2.6 mm Al, which was rounded to 2.5 mm Al for selection of DCFs.

3.3.3 General Electric X-Ray Machine, 1988 to 1993

In March 1988 a new General Electric Company (GE) X-ray system was installed at Fernald. A chest technique chart from 1988 indicates that the techniques were developed by the Eastman Kodak Company for its Lanex Regular screen/film system, and that a 12:1 grid was to be used. The technique listed for the 23 cm PA chest is 100 kVp, 200 mA, and 0.025 second; that for the LAT chest was110 kVp, 200 mA, and 0.083 second (Gibson 1988).

The Food and Drug Administration (FDA) performed two sets of ESE measurements on this machine in 1991 and 1993 that resulted in ESEs of 12.2 mR (Bolen 1991) and 15.3 mR (Bolen 1993). The HVL measured in 1993 was 2.5 mm Al at 80 kVp. Using Table B-2 of NCRP Report 102 (NCRP 1997), this amount of total filtration would result in an HVL of 3.0 mm of Al at 100 kVp, the setting that would have been used for the PA chest. The organ doses for this period, then, are based on the higher of the two measured ESEs (15.3 mR) and an HVL of 3.0 mm Al for 100 kVp. Converting the ESE to incident air kerma using the equation in ORAUT-OTIB-0006 (ORAUT 2011a) results in an incident air kerma of 1.34×10^{-2} cGy for the PA chest, and 3.35×10^{-2} cGy for the LAT chest.

3.3.4 General Electric X-Ray Machine, 1994 to 2006

In 1993, Fernald changed the film-screen combination for chest X-rays to the Kodak Insight Thoracic Imaging System (Hinnefeld 1995), which required a change in the technique factors even though the X-ray machine remained the same. This chest imaging system consisted of two different screens in the front and the back of the film cassette and a dual emulsion film designed to be exposed by the respective front and back screens with zero crossover between the two. The design was intended to provide a longer contrast scale in the resulting image so the radiologist could better visualize both the high anatomical contrast of the lung fields and the low anatomical contrast of the mediastinum and heart in the same exposure, which has always been an imaging challenge. The slower speed of the overall film-screen system was offset by the additional diagnostic information in the images.

The FDA performed three sets of ESE measurements on this machine from 1995 to 1997, resulting in ESEs of 28.0 mR (Bolen 1995), 32.2 mR (Barnett 1997), and 30.2 mR (Bolen 2000). The HVL was reported in 1995 and 1999 as 2.9 and 2.8 mm Al at 90 kVp in those years, respectively. Using Table B-2 of NCRP Report 102 (NCRP 1997), this amount of total filtration would result in an HVL of 3.5 mm of Al at 110 to 120 kVp, the setting that was used for the PA chest in this period (Bolen 1995, 2000). FDA reported that they thought the measured ESE of 32.2 mR in 1997 could be lowered and worked with Fernald to lower it to 19.2 mR by increasing the kVp and lowering the mAs (Barnett 1997). Therefore, the organ doses for this period are based on the highest of the three measured ESEs (after correction) of 30.2 mR measured in 1999 and an HVL of 3.5 mm Al for 120 kVp. Converting the ESE to incident air kerma using the equation in ORAUT-OTIB-0006 (ORAUT 2011a) results in an incident air kerma of 2.65×10^{-2} cGy for the PA chest, and 6.625×10^{-2} cGy for the LAT chest.

3.3.5 2007 to Present

All the buildings at Fernald were demolished in approximately 2006. It is assumed that the X-ray equipment was removed at this time. Any worker X-rays after 2007 should be assumed to have been taken off the site at local area clinics or hospitals and should not be included in dose reconstruction in accordance with ORAUT-OTIB-0079, *Guidance on Assigning Occupational X-Ray Dose Under EEOICPA for X-Rays Administered Off Site* (ORAUT 2011b).

3.4 ORGAN DOSE CALCULATIONS

Organ and skin dose equivalents for each chest projection were calculated as described in ORAUT-OTIB-0006 (ORAUT 2011a) using the site-specific information from Fernald that is described in the previous sections. The organ dose equivalents are listed in Tables 3-3 and 3-4. The tissue at risk for chronic lymphocytic leukemia is the B-lymphocytes. The dose equivalent to the B-lymphocytes was determined using the method in ORAUT-OTIB-0082, *Dose Reconstruction Method for Chronic Lymphocytic Leukemia* (ORAUT 2012), site-specific information, and International Commission on Radiological Protection (ICRP) Publication 34 DCFs (ICRP 1982). The dose distributions and corresponding statistical parameters for the dose to the B-lymphocytes for each projection and period is listed in Table 3-5. The skin dose guidance for determining dose equivalent for the skin is found in Table 3-6, and the skin dose equivalents to all areas of skin are listed in Tables 3-7 and 3-8.

3.5 UNCERTAINTY

ORAUT-OTIB-0006 (ORAUT 2011a) lists the major sources of uncertainty in X-ray output intensity and their subsequent effects on 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 source-to-skin distance 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 from differences of standard chest thickness of ±7.5 cm.

These uncertainties are assumed to be random; therefore, the combined statistical uncertainty was calculated as the square root of the sum of the squares of all the uncertainties, which is ±28.9%. Rounding this up to ±30% provides an adequate and suitably conservative indication of uncertainty. Therefore, a total combined standard uncertainty of ±30% can be assumed for a derived dose equivalent to an individual organ other than the B-lymphocytes. Dose reconstructors should, therefore, input the organ dose equivalent as the mean of a normal distribution with a standard uncertainty of ±30%.

3.6 ATTRIBUTIONS AND ANNOTATIONS

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

Table 3-3. Organ dose equivalents (rem) for PA and LAT/OBL chest radiography, 1952 to 1987.[a]

Organ	PA chest 1952–1973	LAT/OBL chest 1952–1973	PA chest 1974–1987	LAT/OBL chest 1974–1987
Thyroid	2.13E-02	5.02E-02	5.44E-04	4.89E-03
Eye/brain	3.91E-03	5.02E-02	5.44E-04	4.89E-03
Ovaries	2.05E-02	2.09E-02	1.70E-05	2.55E-05
Urinary bladder/prostate	2.05E-02	2.09E-02	1.70E-05	9.35E-03
Colon/rectum	2.05E-02	2.09E-02	1.70E-05	2.55E-05
Testes	1.11E-03	1.21E-03	1.70E-07	2.55E-05
Lungs (male)	5.12E-02	7.07E-02	7.12E-03	4.25E-06
Lungs (female)	5.51E-02	8.06E-02	7.67E-03	8.20E-03
Thymus	5.51E-02	8.06E-02	7.67E-03	9.35E-03
Esophagus	5.51E-02	8.06E-02	7.67E-03	9.35E-03
Stomach	5.51E-02	8.06E-02	7.67E-03	9.35E-03
Bone surface	5.51E-02	8.06E-02	7.67E-03	9.35E-03
Liver/gall bladder/spleen/pancreas	5.51E-02	8.06E-02	7.67E-03	9.35E-03
Remainder organs	5.51E-02	8.06E-02	7.67E-03	9.35E-03
Breast	5.99E-03	9.35E-02	8.33E-04	1.08E-02
Uterus	1.82E-02	1.58E-02	2.21E-05	2.55E-05
Bone marrow (male)	1.12E-02	1.36E-02	1.56E-03	1.57E-03
Bone marrow (female)	1.05E-02	1.06E-02	1.46E-03	1.23E-03
Entrance skin[b]	1.65E-01	4.95E-01	2.30E-02	5.74E-02

a. OBL = oblique.
b. Entrance skin dose equivalent (ENSD) is determined by multiplying the incident air kerma by the backscatter factors of 1.35, 1.40, and 1.40 for HVLs of 2.5, 3.0, and 3.5 mm Al, respectively, from NCRP Report 102 (NCRP 1997, Table B-8). Skin doses for all areas of skin are provided in Tables 3-5, 3-6, and 3-7.

Table 3-4. Organ dose equivalents (rem) for PA and LAT/OBL chest radiography, 1988 to 2006.[a]

Organ	PA chest 1988–1993	LAT/OBL chest 1988–1993	PA chest 1994–2006	LAT/OBL chest 1994–2006
Thyroid	6.16E-04	4.46E-03	1.64E-03	1.00E-02
Eye/brain	6.16E-04	4.46E-03	1.64E-03	1.00E-02
Ovaries	2.41E-05	3.02E-05	8.48E-05	1.06E-04
Urinary bladder/prostate	2.41E-05	3.02E-05	8.48E-05	1.06E-04
Colon/rectum	2.41E-05	3.02E-05	8.48E-05	1.06E-04
Testes	1.34E-07	3.35E-06	2.65E-07	6.63E-06
Lungs (male)	6.65E-03	7.91E-03	1.50E-02	1.83E-02
Lungs (female)	7.17E-03	8.94E-03	1.62E-02	2.05E-02
Thymus	7.17E-03	8.94E-03	1.62E-02	2.05E-02
Esophagus	7.17E-03	8.94E-03	1.62E-02	2.05E-02
Stomach	7.17E-03	8.94E-03	1.62E-02	2.05E-02
Bone surface	7.17E-03	8.94E-03	1.62E-02	2.05E-02
Liver/gall bladder/spleen/pancreas	7.17E-03	8.94E-03	1.62E-02	2.05E-02
Remainder organs	7.17E-03	8.94E-03	1.62E-02	2.05E-02
Breast	9.25E-04	9.61E-03	2.41E-03	2.09E-02
Uterus	3.08E-05	3.02E-05	7.95E-05	9.28E-05
Bone marrow (male)	1.57E-03	1.61E-03	3.87E-03	4.04E-03
Bone marrow (female)	1.50E-03	1.27E-03	3.74E-03	3.18E-03
Entrance skin[b]	1.88E-02	4.69E-02	3.71E-02	9.28E-02

a. OBL = oblique.
b. Entrance skin dose equivalent (ENSD) is determined by multiplying the incident air kerma by the backscatter factors of 1.35, and 1.40 for HVLs of 2.5, 3.0, and 3.5 mm Al, respectively, from NCRP Report 102 (NCRP 1997, Table B-8). Skin doses for all areas of skin are provided in Tables 3-5, 3-6, and 3-7.

Table 3-5. IREP dose distributions and corresponding statistical parameters for the dose to the B-lymphocytes.

Projection and Period	IREP Distribution	Parameter 1	Parameter 2	Parameter 3
PA Chest 1952-1973	Weibull 3	2.904482	0.033720	2.66728E-04
LAT Chest 1952-1973	Weibull 3	2.679219	0.044888	2.06358E-04
PA Chest 1974-1987	Weibull 3	2.053958	0.003243	9.46829E-06
LAT Chest 1974-1987	Weibull 3	2.065456	0.003958	7.26643E-06
PA Chest 1988-1993	Weibull 3	2.069225	0.003046	2.43073E-08
LAT Chest 1988-1993	Weibull 3	2.077655	0.003795	1.11464E-05
PA Chest 1994-2006	Weibull 3	2.076798	0.006927	4.18549E-05
LAT Chest 1994-2006	Weibull 3	2.090940	0.008836	2.05336E-05

Table 3-6. Skin dose guidance for PA, LAT, and RAO chest projections, 1952 to 2006.[a]

Area of skin	PA chest guidance ≤1970	LAT chest guidance ≤1970	RAO chest guidance ≤1970	PA chest guidance >1970	LAT chest guidance >1970	RAO chest guidance >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 (0.52m)	RSD (0.52m)	RSD (0.52m)	RSD (0.52m)	RSD (0.52m)	RSD (0.52m)
Back left thigh	RSD (0.52m)	RSD (0.52m)	RSD (0.52m)	RSD (0.52m)	RSD (0.52m)	RSD (0.52m)
Front right thigh	RSD (0.52m)	RSD (0.52m)	RSD (0.52m)	RSD (0.52m)	RSD (0.52m)	RSD (0.52m)
Back right thigh	RSD (0.52m)	RSD (0.52m)	RSD (0.52m)	RSD (0.52m)	RSD (0.52m)	RSD (0.52m)
Left knee and below	RSD (0.86m)	RSD (0.86m)	RSD (0.86m)	RSD (0.86m)	RSD (0.86m)	RSD (0.86m)
Right knee and below	RSD (0.86m)	RSD (0.86m)	RSD (0.86m)	RSD (0.86m)	RSD (0.86m)	RSD (0.86m)
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

Area of skin	PA chest guidance ≤1970	LAT chest guidance ≤1970	RAO chest guidance ≤1970	PA chest guidance >1970	LAT chest guidance >1970	RAO chest guidance >1970
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
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. ENSD = entrance skin exposure; EXSD = exit skin exposure; RSD = remote skin dose.

Table 3-7. Skin dose equivalents (rem) for PA, LAT, and RAO chest projections, 1952 to 1987.[a]

Area of skin	PA chest 1952–1973	LAT chest 1952–1973	RAO chest 1952–1973	PA chest 1974–1987	LAT chest 1974–1987	RAO chest 1974–1987
Right front shoulder	3.6E-03	4.95E-01	2.2E-03	5.E-04	5.74E-02	3.E-04
Right back shoulder	1.65E-01	4.95E-01	4.95E-01	2.30E-02	5.74E-02	5.74E-02
Left front shoulder	3.6E-03	2.2E-03	2.2E-03	5.E-04	3.E-04	3.E-04
Left back shoulder	1.65E-01	2.2E-03	4.95E-01	2.30E-02	3.E-04	5.74E-02
Right upper arm to elbow	1.65E-01	4.95E-01	4.95E-01	2.3E-03	5.74E-02	5.7E-03
Left upper arm to elbow	1.65E-01	2.2E-03	4.95E-01	2.3E-03	3.E-04	5.7E-03
Left hand	1.65E-01	4.95E-02	4.95E-02	2.3E-03	5.7E-03	5.7E-03
Right hand	1.65E-01	4.95E-02	4.95E-02	2.3E-03	5.7E-03	5.7E-03
Left elbow, forearm, wrist	1.65E-01	4.95E-02	4.95E-02	2.3E-03	5.7E-03	5.7E-03
Right elbow, forearm, wrist	1.65E-01	4.95E-02	4.95E-02	2.3E-03	5.7E-03	5.7E-03
Right side of head including ear and temple	1.65E-02	5.02E-02	2.E-04	2.3E-03	5.7E-03	3.E-05
Left side of head including ear and temple	1.65E-02	5.02E-02	4.95E-02	2.3E-03	5.7E-03	5.7E-03
Front left thigh	5.E-05	7.E-05	7.E-05	7.E-06	8.E-06	8.E-06
Back left thigh	5.E-05	7.E-05	7.E-05	7.E-06	8.E-06	8.E-06
Front right thigh	5.E-05	7.E-05	7.E-05	7.E-06	8.E-06	8.E-06
Back right thigh	5.E-05	7.E-05	7.E-05	7.E-06	8.E-06	8.E-06
Left knee and below	2.E-05	2.E-06	2.E-06	2.E-06	3.E-06	3.E-06
Right knee and below	2.E-05	2.E-06	2.E-06	2.E-06	3.E-06	3.E-06
Left side of face	2.13E-02	5.02E-02	4.95E-01	5.E-04	5.7E-03	5.7E-03
Right side of face	2.13E-02	5.02E-02	2.2E-03	5.E-04	5.7E-03	3.E-05
Left side of neck	1.65E-01	5.02E-02	4.95E-01	2.3E-03	5.7E-03	5.7E-03
Right side of neck	1.65E-01	5.02E-02	2.2E-03	2.3E-03	5.7E-03	3.E-05
Back of head	1.65E-02	5.02E-02	4.95E-02	2.3E-03	5.7E-03	5.7E-03
Front of neck	2.13E-02	5.02E-02	5.02E-02	5.E-04	5.7E-03	4.9E-03
Back of neck	1.65E-01	5.02E-02	4.95E-01	2.3E-03	5.7E-03	5.7E-03
Front torso: base of neck to end of sternum	3.6E-03	8.06E-02	2.2E-03	5.E-04	9.4E-03	3.E-04
Front torso: end of sternum to lowest rib	3.6E-03	8.06E-02	2.2E-03	5.E-04	9.4E-03	3.E-04
Front torso: lowest rib to iliac crest	3.6E-03	8.06E-02	2.2E-03	5.E-05	9.E-04	3.E-05
Front torso: iliac crest to pubis	4.E-04	8.1E-03	2.E-04	5.E-05	9.E-04	3.E-05
Back torso: base of neck to mid-back	1.65E-01	8.06E-02	4.95E-01	2.30E-02	9.4E-03	5.74E-02
Back torso: mid-back to lowest rib	1.65E-01	8.06E-02	4.95E-01	2.30E-02	9.4E-03	5.74E-02
Back torso: lowest rib to iliac crest	1.65E-01	8.06E-02	4.95E-01	2.3E-03	9.E-04	5.7E-03
Back torso: buttocks (Iliac crest and below)	1.65E-02	8.1E-03	4.95E-02	2.3E-03	9.E-04	5.7E-03
Right torso: base of neck to end of sternum	1.65E-01	4.95E-01	2.2E-03	2.30E-02	5.74E-02	3.E-04
Right torso: end of sternum to lowest rib	1.65E-01	4.95E-01	2.2E-03	2.30E-02	5.74E-02	3.E-04
Right torso: lowest rib to iliac crest	1.65E-01	4.95E-01	2.2E-03	2.3E-03	5.7E-03	3.E-05
Right torso: iliac crest to pubis (right hip)	1.65E-02	4.95E-02	2.E-04	2.3E-03	5.7E-03	3.E-05
Left torso: base of neck to end of sternum	1.65E-01	2.2E-03	4.95E-01	2.30E-02	3.E-04	5.74E-02

Area of skin	PA chest 1952–1973	LAT chest 1952–1973	RAO chest 1952–1973	PA chest 1974–1987	LAT chest 1974–1987	RAO chest 1974–1987
Left torso: end of sternum to lowest rib	1.65E-01	2.2E-03	4.95E-01	2.30E-02	3.E-04	5.74E-02
Left torso: lowest rib to iliac crest	1.65E-01	2.2E-03	4.95E-01	2.3E-03	3.E-05	5.7E-03
Left torso: iliac crest to pubis (left hip)	1.65E-02	2.E-04	4.95E-02	2.3E-03	3.E-05	5.7E-03

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

Table 3-8. Skin dose equivalents (rem) and guidance for PA, LAT, and RAO chest projections, 1988 to 2006.[a]

Area of skin	PA chest 1988–1993	LAT chest 1988–1993	RAO chest 1988–1993	PA chest 1994–2006	LAT chest 1994–2006	RAO chest 1994–2006
Right front shoulder	5.E-04	4.69E-02	2.E-04	1.1E-03	9.28E-02	6.E-04
Right back shoulder	1.88E-02	4.69E-02	4.69E-02	3.71E-02	9.28E-02	9.28E-02
Left front shoulder	5.E-04	2.E-04	2.E-04	1.1E-03	6.E-04	6.E-04
Left back shoulder	1.88E-02	2.E-04	4.69E-02	3.71E-02	6.E-04	9.28E-02
Right upper arm to elbow	1.9E-03	4.69E-02	4.7E-03	3.7E-03	9.28E-02	9.3E-03
Left upper arm to elbow	1.9E-03	2.E-04	4.7E-03	3.7E-03	6.E-04	9.3E-03
Left hand	1.9E-03	4.7E-03	4.7E-03	3.7E-03	9.3E-03	9.3E-03
Right hand	1.9E-03	4.7E-03	4.7E-03	3.7E-03	9.3E-03	9.3E-03
Left elbow, forearm, wrist	1.9E-03	4.7E-03	4.7E-03	3.7E-03	9.3E-03	9.3E-03
Right elbow, forearm, wrist	1.9E-03	4.7E-03	4.7E-03	3.7E-03	9.3E-03	9.3E-03
Right side of head including ear and temple	1.9E-03	4.7E-03	2.E-05	3.7E-03	9.3E-03	6.E-05
Left side of head including ear and temple	1.9E-03	4.7E-03	4.7E-03	3.7E-03	9.3E-03	9.3E-03
Front left thigh	6.E-06	7.E-06	7.E-06	1.E-05	2.E-05	2.E-05
Back left thigh	6.E-06	7.E-06	7.E-06	1.E-05	2.E-05	2.E-05
Front right thigh	6.E-06	7.E-06	7.E-06	1.E-05	2.E-05	2.E-05
Back right thigh	6.E-06	7.E-06	7.E-06	1.E-05	2.E-05	2.E-05
Left knee and below	2.E-06	3.E-06	3.E-06	5.E-06	6.E-06	6.E-06
Right knee and below	2.E-06	3.E-06	3.E-06	5.E-06	6.E-06	6.E-06
Left side of face	6.E-04	4.7E-03	4.7E-03	1.6E-03	9.3E-03	9.3E-03
Right side of face	6.E-04	4.7E-03	2.E-05	1.6E-03	9.3E-03	6.E-05
Left side of neck	1.9E-03	4.7E-03	4.7E-03	3.7E-03	9.3E-03	9.3E-03
Right side of neck	1.9E-03	4.7E-03	2.E-05	3.7E-03	9.3E-03	6.E-05
Back of head	1.9E-03	4.7E-03	4.7E-03	3.7E-03	9.3E-03	9.3E-03
Front of neck	6.E-04	4.7E-03	4.46E-03	1.6E-03	9.3E-03	1.00E-02
Back of neck	1.9E-03	4.7E-03	4.7E-03	3.7E-03	9.3E-03	9.3E-03
Front torso: base of neck to end of sternum	5.E-04	8.9E-03	2.E-04	1.1E-03	2.05E-02	6.E-04
Front torso: end of sternum to lowest rib	5.E-04	8.9E-03	2.E-04	1.1E-03	2.05E-02	6.E-04
Front torso: lowest rib to iliac crest	5.E-05	9.E-04	2.E-05	1.E-04	2.1E-03	6.E-05
Front torso: iliac crest to pubis	5.E-05	9.E-04	2.E-05	1.E-04	2.1E-03	6.E-05
Back torso: base of neck to mid-back	1.88E-02	8.9E-03	4.69E-02	3.71E-02	2.05E-02	9.28E-02
Back torso: mid-back to lowest rib	1.88E-02	8.9E-03	4.69E-02	3.71E-02	2.05E-02	9.28E-02
Back torso: lowest rib to iliac crest	1.9E-03	9.E-04	4.7E-03	3.7E-03	2.1E-03	9.3E-03
Back torso: buttocks (Iliac crest and below)	1.9E-03	9.E-04	4.7E-03	3.7E-03	2.1E-03	9.3E-03
Right torso: base of neck to end of sternum	1.88E-02	4.69E-02	2.E-04	3.71E-02	9.28E-02	6.E-04
Right torso: end of sternum to lowest rib	1.88E-02	4.69E-02	2.E-04	3.71E-02	9.28E-02	6.E-04
Right torso: lowest rib to iliac crest	1.9E-03	4.7E-03	2.E-05	3.7E-03	9.3E-03	6.E-05
Right torso: iliac crest to pubis (right hip)	1.9E-03	4.7E-03	2.E-05	3.7E-03	9.3E-03	6.E-05
Left torso: base of neck to end of sternum	1.88E-02	2.E-04	4.69E-02	3.71E-02	6.E-04	9.28E-02

Area of skin	PA chest 1988–1993	LAT chest 1988–1993	RAO chest 1988–1993	PA chest 1994–2006	LAT chest 1994–2006	RAO chest 1994–2006
Left torso: end of sternum to lowest rib	1.88E-02	2.E-04	4.69E-02	3.71E-02	6.E-04	9.28E-02
Left torso: lowest rib to iliac crest	1.9E-03	2.E-05	4.7E-03	3.7E-03	6.E-05	9.3E-03
Left torso: iliac crest to pubis (left hip)	1.9E-03	2.E-05	4.7E-03	3.7E-03	6.E-05	9.3E-03

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

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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.

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

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.

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 gray equals 1 joule per kilogram or 100 rads.

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.

lumbar spine
The vertebrae of the lower back.

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 radiation absorbed dose.

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.

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 (R, sometimes r)

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 degrees Celsius 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).

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.