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Oak Ridge Gaseous Diffusion Plant (K-25) – Occupational Medical Dose

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PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
06/29/2004	00	New technical basis document for the Oak Ridge Gaseous Diffusion (K-25) plant – Occupational Medical Dose. First approved issue. Initiated by Jay J. Maisler.
11/07/2006	00 PC-1	Approved page change revision to update required language on pages 4 and 5 in Section 3.1. Updates acronyms and abbreviations on page 3. Adds a Purpose Section and a Scope Section on page 5. No sections were deleted. No further changes occurred as a result of formal internal review. No changes required to this document due to Worker Outreach comments. This revision results in no change to the assigned dose and no PER is required. Training as required by Task Manager. Initiated by Paul A. Szalinski. Approval: Signature on File 10/24/2006 Paul A. Szalinski, Document Owner Signature on File 10/20/2006 John M. Byrne, Task 3 Manager Signature on File 10/24/2006 Edward F. Maher, Task 5 Manager Signature on File 10/23/2006 Kate Kimpan, Project Director Signature on File 11/07/2006 James W. Neton, Associate Director for Science
03/28/2013	01	Revision to update doses according to site-specific information and recently revised ORAUT-OTIB-0006. Incorporates resolutions to Sanford Cohen & Associates comments. Also incorporates formal internal and NIOSH review comments. Constitutes a total rewrite of the document. Training required: As determined by the Objective Manager. Initiated by Michalene Rodriguez.
11/18/2019	02	Revision initiated to (1) update doses to the present era, (2) provide directions about lumbar spine examination records, and (3) provide IREP dose distributions and statistical parameters for B-lymphocytes (Table 3-3). Incorporates formal internal and NIOSH review comments. Constitutes a total rewrite of the document. Training required: As determined by the Objective Manager. Initiated by Michalene Rodriguez.

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ACRONYMS AND ABBREVIATIONS

AWE	atomic weapons employer
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
ETTP	East Tennessee Technology Park
EXSD	exit skin dose
GE	General Electric
Gy	gray
HVL	half-value layer
in.	inch
IREP	Interactive RadioEpidemiology Program
kVp	peak kilovoltage
LAT	lateral
mA	milliampere
mm	millimeter
NIOSH	National Institute for Occupational Safety and Health
ORAU	Oak Ridge Associated Universities
PA	posterior-anterior
PER	Program Evaluation Report
PFG	photofluorography
RSD	remote skin dose
s	second
SEC	Special Exposure Cohort
SRDB Ref ID	Site Research Database Reference Identification (number)
TBD	Technical basis document
U.S.C.	United States Code
yr	year
§	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 Department of Energy (DOE) or Atomic Weapons Employer (AWE) facilities or categories of DOE or AWE facilities. They will be revised in the event additional relevant information is obtained about the affected DOE or AWE facility(ies). These documents may be used to assist NIOSH staff in the evaluation of Special Exposure Cohort (SEC) petitions and the completion of the individual work required for each dose reconstruction.

In this document the word "facility" is used to refer to an area, building, or group of buildings that served a specific purpose at a DOE or AWE facility. It does not mean nor should it be equated to an "AWE facility" or a "DOE facility." The terms AWE and DOE facility are defined in sections 7384l(5) and (12) of the Energy Employees Occupational Illness Compensation Program Act of 2000 (EEOICPA), respectively. An AWE facility means "a facility, owned by an atomic weapons employer, that is or was used to process or produce, for use by the United States, material that emitted radiation and was used in the production of an atomic weapon, excluding uranium mining or milling." 42 U.S.C. § 7384l(5). On the other hand, a DOE facility is defined 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 [DOE] (except for buildings, structures, premises, grounds, or operations … pertaining to the Naval Nuclear Propulsion Program);" and with regard to which DOE has or had a proprietary interest, or "entered into a contract with an entity to provide management and operation, management and integration, environmental remediation services, construction, or maintenance services." 42 U.S.C. § 7384l(12). The Department of Energy (DOE) determines whether a site meets the statutory definition of an AWE facility and the Department of Labor (DOL) determines if a site is a DOE facility and, if it is, designates it as such.

Accordingly, a Part B claim for benefits must be based on an energy employee's eligible employment and occupational radiation exposure at a DOE or AWE facility during the facility's designated time period and location (i.e., covered employee). After DOL determines that a claim meets the eligibility requirements under EEOICPA, DOL transmits the claim to NIOSH for a dose reconstruction. EEOICPA provides, among other things, guidance on eligible employment and the types of radiation exposure to be included in an individual dose reconstruction. Under EEOICPA, eligible employment at a DOE facility includes individuals who are or were employed by DOE and its predecessor agencies, as well as their contractors and subcontractors at the facility. Unlike the abovementioned statutory provisions on DOE facility definitions that contain specific descriptions or exclusions on facility designation, the statutory provision governing types of exposure to be included in dose reconstructions for DOE covered employees only requires that such exposures be incurred in the performance of duty. As such, NIOSH broadly construes radiation exposures incurred in the performance of duty to include all radiation exposures received as a condition of employment at covered DOE facilities in its dose reconstructions for covered employees. For covered employees at DOE facilities, individual dose reconstructions may also include radiation exposures related to the Naval Nuclear Propulsion Program at DOE facilities, if applicable. No efforts are made to determine the eligibility of any fraction of total measured exposure for inclusion in dose reconstruction.

NIOSH does not consider the following types of exposure as those incurred in the performance of duty as a condition of employment at a DOE facility. Therefore these exposures are not included in dose reconstructions for covered employees (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

3.1.1 Purpose

This technical basis document (TBD) details historical practices and provides the basis for organ dose from medical X-ray procedures for occupational health screening at K-25.

Over the years, the Oak Ridge Gaseous Diffusion Plant has been known as the K-25 Plant, the Oak Ridge K-25 Site, and now the East Tennessee Technology Park (ETTP). For convenience, this document uses K-25 for earlier years and ETTP for later years.

3.1.2 Scope

The K-25 occupational health and safety program required pre-employment, periodic physical, and termination health monitoring examinations from the beginning of its operation in 1944 (Author unknown 1946, p. 94; Author unknown 1947, p. 2). These examinations typically included chest X-rays. The doses from these procedures depended on the characteristics of the X-ray machine and the techniques used. Site-specific information about the K-25 X-ray screening program is used to the extent it is known.

3.1.3 Special Exposure Cohort

This document provides supporting technical data to assist in the reconstruction of occupational medical doses. K-25 is one of the original sites that was designated by Congress as part of the Special Exposure Cohort (SEC) under EEOICPA [42 U.S.C. § 7384l(14)]. This designation is as follows:

> *(A) The employee was so employed for a number of work days aggregating at least 250 work days before February 1, 1992, at a gaseous diffusion plant located in Paducah, Kentucky, Portsmouth, Ohio, or Oak Ridge, Tennessee, and, during such employment—*
>
> > *(i) was monitored through the use of dosimetry badges for exposure at the plant of the external parts of employee's body to radiation; or*
> >
> > *(ii) worked in a job that had exposures comparable to a job that is or was monitored through the use of dosimetry badges.*

Dose reconstruction guidance in this document is presented to provide a technical basis for dose reconstructions for nonpresumptive cancers that are not covered in the SEC class through January 31, 1992. Dose reconstructions for individuals who were employed at K-25 before February 1, 1992, but who do not qualify for inclusion in the SEC, can be performed using this guidance.

3.2 BACKGROUND, EXAMINATION TYPES, AND FREQUENCIES

Before the K-25 Medical Dispensary was operational, the workers had their pre-employment examinations at the Medical Services Building of the Oak Ridge Hospital (Author unknown 1946, p. 88). Built by the Army Corps of Engineers, the Oak Ridge Hospital opened their doors on November 17, 1943 (Brookshire and Wallace 2009). Little is known about the X-ray machines at the Oak Ridge Hospital, but the dose from pre-employment chest X-rays taken there should be included in dose reconstruction because it is a covered facility (DOE 2019). Unless otherwise noted, dose reconstructors should assume X-rays were taken at the Oak Ridge Hospital from November 17, 1943 through September, 1944. Before the opening of the Oak Ridge Hospital, no dose from occupational X-rays should be assigned.

The Carbide and Carbon Chemicals Corporation organized a medical department at K-25 in April, 1944 (Author unknown 1946, p. 88). Pre-employment examinations were conducted in the Carbide and Carbon Administration Building from April, 1944 to July, 1944 (Author unknown 1946, pp. 87, 88). It is doubtful that this building had X-ray capabilities, and it is assumed workers were sent to the Oak Ridge Hospital for X-rays during this time.

The medical department at the main dispensary began operating in July, 1944. Due to the rise in the number of X-ray procedures required for diagnostic purposes, X-ray equipment was installed at the dispensary and available beginning October, 1944, and a photoroentgen unit was later added in April, 1945 (Author unknown 1946, p. 89). Workers from the Ford, Bacon, and Davis Company and the H. K. Ferguson Company (Fercleve Corporation), both contractors, were also examined at the K-25 dispensary (Author unknown 1946, p. 89).

During the early years at K-25, when little was known about health effects of working with uranium, X-ray examinations were performed frequently in an effort to monitor worker health, perhaps as often as every 6 months (Kammer 1948, p. 8). During recheck examinations, individuals in special hazard groups may have received an X-ray examination (Author unknown 1947). In addition, it was noted that X-rays were performed on individuals who received a major acute exposure from uranium (Author unknown 1947). Bocher (1948) writes that workers handling process material might be X-rayed excessively.

Table 3-1 lists the nominal frequency of examinations over the years during which X-rays were required as part of occupational health screening. Some workers might have received these X-rays on a schedule different from that listed in Table 3-1. Dose reconstructors should assign dose according to the X-rays performed for screening listed in the claim file records, and in the absence of records, according to the frequency listed in Table 3-1.

K-25 workers who subsequently worked at Y-12 or X-10 might have had their X-ray records transferred to the Y-12 or X-10 medical departments. Because X-ray records are not typically submitted by Y-12 or X-10 during the initial request, the dose reconstructions of these workers should be completed by (1) assuming the X-ray frequency from Table 3-1 for their K-25 employment, or (2) submitting a repeat request for the X-ray records from Y-12 or X-10. An additional request for X-ray records would only be necessary when the claim is in the best-estimate range.

Other X-rays (i.e., pelvis, lumbar spine, thoracic and cervical spine exams) may have been performed for workers with the potential for exposure to fluoride or fluoride compounds (ORAUT-OTIB-0006 2019, p. 33). Historical evidence of a routine fluorosis screening program at K-25 has not been found. In fact, Cardarelli (2000, p. 82) revealed from a study that was conducted of 297 employee medical records, ranging in date from 1944 through 1989, a total of 2,188 X-ray records were evaluated; of the 2,188 records, only 50 were lumbar spine X-rays (2.28%) and 7 were pelvic exams (0.32%). Due to the low number of lumbar spine and pelvic exams from this study, it appears a fluorosis screening program at K-25 probably did not exist.

These additional radiographic examinations may have been nonoccupational; in the sense that they were necessitated by illness or injury and were not part of the employee occupational health screening process. For example, a review of some claim file records reveal lumbar spine X-rays can be traced to occurrence of injury, complaints, or symptoms of back pain in the respective workers' records, and therefore do not meet the definition of X-ray screening (Thomas 2015). Thus, if lumbar spine, pelvic, thoracic and cervical spine exams are present in the employee's records, they are not to be used for dose reconstruction purposes.

Table 3-1. Assumed default frequency of screening chest X-rays at K-25 based on review of records and references.

Period	Frequency	Employee	Type
Before November 17, 1943	None	None	None
November 17, 1943–September, 1944	Preemployment[a]	All employees	PFG
October, 1944–1956	Preemployment,[b] annual,[c] and termination[b,c]	All employees[b]	See Section 3.3.1.1
1957–1961[b]	Preemployment,[d] annual,[d] and termination[d]	All employees	PA chest
1962–1970	Preemployment, every 1–2 yr, and termination	Radiation workers >40 years old [d,e]	PA chest
1962–1970	Preemployment, every 2+ yr, and termination	Radiation workers <40 years old[d,e]	PA chest
1971–1986	Preemployment, every 1–2 yr, and termination	Radiation workers >40 years old[e,f]	PA and lateral (LAT) chest
1971–1986	Preemployment, every 2+ yr, and termination	Radiation workers <40 years old[e,f]	PA and LAT chest
1987–2000	Preemployment, annual, and termination	Radiation workers[g]	PA and LAT chest
2001–May 15, 2019	Preemployment, some periodic depending on hazard group, some termination[h,i] Some X-rays might have been taken at a noncovered facility.	Workers in surveillance programs (e.g., HAZWOPER, asbestos, respirator).	PA and LAT chest
May 16, 2019–present	None – all X-rays taken at a noncovered facility.[j]	None	None

a. X-rays taken at the Oak Ridge Hospital
b. Source: Author unknown (1947, p. 2).
c. Semiannually for workers with potential for exposure to uranium dust (Kammer 1948).
d. Source: UCNC (1957, p.11).
e. Source: Author unknown (1964, p. 6).
f. Source: Collins (1988).
g. Source: DOE (1993, p. 95-97).
h. Source: Prater (2015a, p. 3).
i. Source: Prater (2015b, p. 3).
j. Source: Newman (2019).

3.3 EQUIPMENT AND TECHNIQUES

The type of X-ray equipment used at K-25 from the inception of the Medical Dispensary from 1944 through May 15, 2019, is provided below in Section 3.3.1 through Section 3.3.6.

3.3.1 Chest Photofluorography (PFG), April 1945 to 1956

PFG had widespread use throughout the United States for tuberculosis screening in the 1930s and was state-of-the-art medical technology when work began at the K-25 plant as part of the Manhattan Project. Eventually, PFG was phased out in favor of the conventional chest X-ray examination using 14- × 17-in. film.

Before the opening of the K-25 Medical Dispensary the examinations were performed at the Oak Ridge Hospital in Oak Ridge, Tennessee. It is known that the Oak Ridge Hospital had a PFG machine (Gupton et al. 1957, p. 21). It is therefore possible that the preplacement medical X-rays taken at the Oak Ridge Hospital could have been PFG. Unless otherwise noted, preplacement X-rays performed at the Oak Ridge Hospital should be considered stereo PFG and the dose values obtained

from ORAUT-OTIB-0006, *Dose Reconstruction from Occupational Medical X-Ray Procedures* (ORAUT 2019).

A PFG machine was added to the K-25 medical dispensary in April 1945 (Author unknown 1946, p. 89). A stereo PFG was "taken on every person hired by the companies served by the Dispensary" (Author unknown 1947, p. 12). Lyon (1949, p. 7) writes that both the pre-employment and the annual examination were made on the PFG unit at K-25, with "all other chest X-rays" made on a 14- × 17-in. film.

The PFG machine at K-25 was a General Electric (GE) Photoroentgen X-ray machine (Author unknown 1947, p. 12) that was used with a grid to produce miniature 4- × 5-in. stereoscopic posterior-anterior (PA) chest X-rays (Cardarelli 2000). The stereoscopic technique produces two images of the chest (on 4- × 10-in. film) at slightly different angles, resulting in a three-dimensional image of the chest when viewed through a stereoscope (Laughlin et al. 1957). While two references refer to PFG at K-25 on either 4- × 5-in. or 4- × 10-in. film (Cardarelli 2000, and Author unknown 1949, p. 12), the K-25 claim file records indicate some PFG on 70 mm film, another common film type for PFG images (Laughlin et al. 1957).

A survey performed on the machines at K-25 listed the technique factors for PFG as 68 kVp, 200 mA, and 0.75 s with a skin dose rate of 6.4 R (Gupton et al. 1957, p. 22). It is assumed that this technique is for stereo projection based on the notation that appears to indicate the time was applied twice. The survey does not include half-value layer (HVL) or total filtration information, so a HVL of 2.5 mm Al at 68 kVp is assumed for dose reconstruction. Based on the information provided, this dose was determined to be a free in air dose and was converted to incident air kerma using Equation 4-1 of ORAUT-OTIB-0006 (ORAUT 2019). This results in an incident air kerma of 5.61 cGy for stereo PFG.

The DCFs applied to calculate organ dose are provided in ORAUT-OTIB-0006, Table B-2 (ORAUT 2019) with the exception of those provided below in Table 3-2. Table 3-2 also provides the factors from Tables B-7 and B-8 of NCRP Report 102 (NCRP 1989) used to calculate skin dose for PFG procedures. The DCFs used for organ dose calculation for the ovaries, testes and uterus are the DCFs for the respective organs for a PA Abdominal projection from ICRP Publication 34 (1982). The DCFs for the urinary bladder/prostate and colon/rectum are based on using the ovaries as a surrogate organ and therefore, also uses the DCF for ovaries for a PA abdominal projection. The use of the abdominal DCFs for these organs accounts for poor collimation of X-ray beams during this timeframe. Note: this is a difference from OTIB-0006 default which uses measured doses for these organs for PFG.

As noted above, the film size for the PFG is 4- × 5-in (10.16 cm × 12.7 cm) which must be taken into account when determining the Back Scatter Factor and Average Percentage Depth Doses. Table B-8 of NCRP Report 102 (NCRP 1989) provides these factors for the following field sizes in cm: 0, 15 × 15, and 35 × 35. Interpolation between the 0 field and 15 × 15 cm field and taking into account the 2.5 mm HVL, results in a BSF of 1.18 and ADD of 6.9 as indicated below.

3.3.1.1 Dose Reconstruction Guidance

Before 1957, the exam type is often unclear in records provided by the DOE. For instance the phrase "P.A. view of the chest" is recorded frequently, but this can imply either a conventional 14- × 17-in. or a stereoscopic PA PFG X-ray. In a past study, films located in the film jackets for several workers with employment before 1957 were measured. The results reveal that approximately 77% of the X-ray exams were 4- × 10-in. PFG examinations. Because the difference in size affects assigned dose, NIOSH has asked K-25 to clarify whether "P.A. view of the chest" means a 4- × 10-in. film (PFG) or a 14- × 17-in. film by actually looking into the film jackets of claimants and documenting the X-ray type before submitting the records to NIOSH (Nelson 2014).

Table 3-2. Organ dose correction factors and other factors to calculate skin dose for PFG exams.

Organ/factor	DCF/skin calculation factors
Ovaries[a]	1.68E–01
Urinary bladder/prostate[b]	1.68E–01
Colon/rectum[b]	1.68E–01
Testes[c]	9.10E–03
Uterus[d]	1.49E–01
Back Scatter Factor (BSF)[e]	1.18
Absorption Factor (AF)[f]	50.95
Average Percentage Depth Doses (ADD)[g]	6.9

a. Ovaries DCF for PA Abdominal used to account for poor collimation.
b. Ovaries DCF for PA Abdominal as surrogate to account for poor collimation.
c. Testes DCF for PA Abdominal used to account for poor collimation.
d. Uterus DCF for PA Abdominal used to account for poor collimation.
e. BSF from NCRP 102, Table B.8, based on 2.5 mm HVL and 10.16 cm X 12.7 cm field size.
f. AF from NCRP 102, Table B.7, based on 2.5 mm HVL, 24 cm Tissue Thickness for PA.
g. ADD from NCRP 102, Table B.8, based on 2.5 mm HVL, 10.16 cm X 12.7 cm field size, and 12 cm depth for PA.

For that reason, between October, 1944 and December, 1956, dose reconstructors should follow the guidance below.

X-ray records absent
**Assume PFG and frequency listed in Table 3-1.*

X-ray records provided
**Notation on X-ray record should indicate the size of the film, i.e. 4- x 5-in, 4- x 10-in., 14- x 17-in or 70 mm. Film size/type should indicate whether PFG exam or the conventional 14- x 17-in. film was performed.*

X-ray records provided, but size of film not noted
**Assume all "PA Chest X-rays are PFG exams when the POC is <45%.*

**If the POC is > or equal to 45%, then make a request to the site that the film size be assessed for accurate identification for each chest X-ray prior to 1957.*

There is no evidence of PFGs performed at K-25 after 1956 from a review of claim file records, which corroborates other information on K-25 (Cardarelli 2000; Cardarelli et al. 2002). The organ doses listed in Table 3-10 and Table 3-11 are based on the assumption of stereo PFG.

3.3.2 Chest Radiography, October, 1944 to 1961

A Westinghouse machine was used to produce 14- × 17-in. chest radiographs (Author unknown 1947, p. 12). The radiographs were used to investigate suspicious areas on PFG images, so it is possible that some employees had both PFG and conventional chest X-rays from 1944 to 1956. After 1956, only conventional PA chest radiographs were taken, which substantially reduced radiation dose per examination.

The 1957 survey (Gupton et al. 1957, p. 22) provides technique factors and dose rates for conventional PA chest radiographs on 14- × 17-in. for the Westinghouse machine at K-25. According to the survey, PA chests were performed at 65 kVp, 200 mA, and 0.1 s with a skin dose of 55 mR. Based on the information provided, this dose rate was determined to be a free in air dose and was converted to incident air kerma using Equation 4-1 of ORAUT-OTIB-0006 (ORAUT 2019). This results in an incident air kerma of 4.82E–02 cGy. The survey does not include HVL or total filtration information, so an HVL of 2.0 mm Al at 65 kVp is assumed for dose reconstruction.

The DCFs applied to calculate organ dose are provided in Table 3-3 below. The DCFs have been selected based on the 2.0 mm HVL and based on the assumption poor collimation was used when X-rays were performed during this time period. The table also provides the factors from Tables B-7 and B-8 of NCRP Report 102 (NCRP 1989) used to calculate skin dose. The organ doses for this time period are listed in Table 3-10 and Table 3-11.

Table 3-3. Organ dose correction factors and other factors to calculate skin dose for 1944–1961.

Organ/factor	DCF/skin calculation factors
Thyroid	1.51E–01
Eye/brain	2.10E–02
Ovaries[a]	1.15E–01
Urinary bladder/ prostate	1.15E–01
Colon/rectum	1.15E–01
Testes[b]	5.70E–03
Lung (male)	3.35E–01
Lung (female)	3.55E–01
Liver/gall bladder/spleen/ pancreas	3.55E–01
Thymus	3.55E–01
Esophagus	3.55E–01
Stomach	3.55E–01
Bone Surface	3.55E–01
Remainder	3.55E–01
Breast	3.20E–02
Uterus[c]	1.03E–01
Bone marrow (male)	6.90E–02
Bone marrow (female)	6.30E–02
Back Scatter Factor (BSF)[d]	1.32
Absorption Factor (AF)[e]	58.3
Average Percentage Depth Doses (ADD)[f]	12.2

a. Ovaries DCF for PA Abdominal used to account for poor collimation.
b. Testes DCF for PA Abdominal used to account for poor collimation.
c. Uterus DCF for PA Abdominal used to account for poor collimation.
d. BSF from NCRP 102, Table B.8, based on 2.0 mm HVL and 35 × 35 cm field size.
e. AF from NCRP 102, Table B.7, based on 2.0 mm HVL, 24 cm Tissue Thickness for PA.
f. ADD from NCRP 102, Table B.8, based on 2.0 mm HVL, 35 × 35 cm field size, and 12 cm depth for PA.

3.3.3 Chest Radiography, 1962 to 1970

A Westinghouse 300-mA machine replaced the 200-mA machine in 1962 (Cardarelli 2000; Cardarelli et al. 2002). No information on either technique factors or beam measurements has been found for the Westinghouse machine presumably installed in 1962. Therefore, the incident air kerma comes from Cardarelli (2000) for this period. As recommended in ORAUT-OTIB-0006 (ORAUT 2019), poor collimation is assumed for this period. The DCFs used in calculating the dose equivalents from chest X-rays are listed in ORAUT-OTIB-0006 (ORAUT 2019), Table B-2, with the exception of those listed below in Table 3-4.

The DCFs have been selected based on the 2.5 mm HVL. The table also provides the factors from Tables B-7 and B-8 of NCRP Report 102 (NCRP 1989) used to calculate skin dose. Organ dose information is provided in Table 3-10 and Table 3-11.

Table 3-4. Organ dose correction factors and other factors to calculate skin dose for 1962–1970.

Organ/factor	DCF/other factors
Ovaries[a]	1.68E–01
Urinary bladder/prostate	1.68E–01
Colon/rectum	1.68E–01
Testes[b]	9.10E–03
Uterus[c]	1.49E–01
Back Scatter Factor (BSF)[d]	1.35
Absorption Factor (AF)[e]	50.95
Average Percentage Depth Doses (ADD)[f]	14.1

a. Ovaries DCF for PA Abdominal used to account for poor collimation.
b. Testes DCF for PA Abdominal used to account for poor collimation.
c. Uterus DCF for PA Abdominal used to account for poor collimation.
d. BSF from NCRP 102, Table B.8, based on 2.5 mm HVL and 35 × 35 cm field size.
e. AF from NCRP 102, Table B.7, based on 2.5 mm HVL, 24 cm Tissue Thickness for PA.
f. ADD from NCRP 102, Table B.8, based on 2.5 mm HVL, 35 × 35 cm field size, and 12 cm depth for PA.

3.3.4 Chest Radiography, 1971 to 1986

In the early 1970s, a lateral (LAT) chest projection was added to the chest X-ray examination procedure (Cardarelli 2000). The claim file records do not always indicate the LAT chest projection, but there is a change in the notation for the mid- to late 1970s from "PA chest" to "Chest," which presumably included two projections (PA and LAT). Dose reconstructors should assign dose from both a PA and LAT chest for this period according to the dose values provided in Table 3-10 and Table 3-12.

The X-ray machine used in this period is presumed to be the same as that for 1962 to 1970, the Westinghouse machine. However, because no information from this machine has been found, the incident air kerma comes from Cardarelli (2000) for this period. As recommended in ORAUT-OTIB-0006 (ORAUT 2019), good collimation is assumed for this period.

The DCFs applied to calculate organ dose is provided in ORAUT-OTIB-0006 (ORAUT 2019) in Table B-3 for the PA and LAT chest, after 1985, based on this period having proper collimation of the X-ray beam and a HVL of 4 mm. Table 3-5 provides the factors from Tables B-7 and B-8 of NCRP Report 102 (NCRP 1989) used to calculate skin dose for chest X-ray procedures.

Table 3-5. Skin calculation factors – PA and LAT chest for 1971 to 1986.

Factor	PA	LAT
Back Scatter Factor (BSF)[a]	1.42	1.42
Absorption Factor (AF)[b]	32.66	148.4
Average Percentage Depth Doses (ADD)[c]	19.3	9.325

a. BSF from NCRP 102, Table B.8, based on 4.0 mm HVL and 35 × 35 cm field size.
b. AF from NCRP 102, Table B.7, based on 4.0 mm HVL, 24 cm Tissue Thickness for PA and 34 cm Tissue Thickness for LAT.
c. ADD from NCRP 102, Table B.8, based on 4.0 mm HVL, 35 × 35 cm field size, 12 cm depth for PA and 17 cm depth for LAT.

3.3.5 Chest Radiography, 1987 to 2000

In 1988, the Food and Drug Administration performed a survey of the Bennett general-purpose X-ray machine that had been installed "recently" at K-25 (Collins 1988). While the exact date of installation is not known, Cardarelli (2000) and Cardarelli et al. (2002) state that a new machine was installed in 1987. They mention the Bennett machine, but also mention a Westinghouse machine in several places. It is assumed that a Bennett machine was installed, not a Westinghouse machine. The significance for dose reconstruction is that the Bennett machines used high-frequency generators in

their designs. However, no other specific information is available about the Bennett machine or the technique factors used, so the incident air kerma comes from Cardarelli (2000) for this period. During this period, environmental restoration workers were part of the medical surveillance program, which included a PA and LAT chest X-ray for pre-employment, annual, and termination exams (DOE 1993). Dose values for this period are listed in Table 3-10 and Table 3-12.

The DCFs applied to calculate organ dose is provided in ORAUT-OTIB-0006 (ORAUT 2019) in Table B-3 for the PA and LAT chest for 1986 and later based on this period having proper collimation of the X-ray beam and a HVL of 4 mm. Table 3-6 provides the factors from Tables B-7 and B-8 of NCRP Report 102 (NCRP 1989) used to calculate skin dose for chest X-ray procedures.

Table 3-6. Skin calculation factors – PA and LAT chest for 1987 to 2000.

Factor	PA	LAT
Back Scatter Factor (BSF)[a]	1.42	1.42
Absorption Factor (AF)[b]	32.66	148.4
Average Percentage Depth Doses (ADD)[c]	19.3	9.325

a. BSF from NCRP 102, Table B.8, based on 4.0 mm HVL and 35 × 35 cm field size.
b. AF from NCRP 102, Table B.7, based on 4.0 mm HVL, 24 cm Tissue Thickness for PA and 34 cm Tissue Thickness for LAT.
c. ADD from NCRP 102, Table B.8, based on 4.0 mm HVL, 35 × 35 cm field size, 12 cm depth for PA and 17 cm depth for LAT.

3.3.6 Chest Radiography, 2001 to May 15, 2019

During this period, pre-employment chest X-rays are required for workers on surveillance programs (e.g., HAZWOPER, asbestos, mercury, cadmium, respirator) (Prater 2015a, p. 3). The periodic exam frequency is variable depending on requirements for the workers in various surveillance programs and physician discretion. Termination physicals may have been offered, and may include X-rays. The chest X-rays were two projection exams, consisting of the PA and LAT chest.

X-ray procedures during this period might have been conducted at noncovered facilities such as the Methodist Medical Center HealthWorks (Prater 2015a, p. 3). According to K-25, when contractors hired large number of employees or the Medical Clinic at ETTP was overloaded, the Methodist Medical Center HealthWorks was used. Accordingly, new hire employees received their X-rays at the Methodist Medical Center HealthWorks during the following periods (Prater 2015a, p. 3):

- 2005 September through October.
- 2006 July through December.
- 2007 January through July; September through November.
- 2008 March through November.
- 2009 February through October.
- 2010 March through April.
- 2014 July and October.

ETTP provided medical services (including X-rays) for some of its subcontractors that entered into contracts with URS/CH2M Oak Ridge (UCOR), the current sitewide operating contractor, for these services. ETTP provided a list of these subcontractors; however, it is expected that these arrangements change over time. ETTP has stated that it provides subcontractor X-ray records as part of its responses to NIOSH EEOICPA requests (Connell 2015, pp. 4-5). As a result, dose reconstructors should still follow the guidance in this document that they should assign dose (provided in Table 3-10 and Table 3-12) according to the X-rays performed for screening listed in the claim file records, and in the absence of records, according to the frequency listed in Table 3-1. The exception to this rule would be workers employed by British Nuclear Fuels Limited (BNFL) between 1997

through 2004. BNFL employees received their physicals and X-ray exams at an occupational health clinic in Oak Ridge (a noncovered facility) (ORAUT 2014a; ORAUT 2017).

The DCFs applied to calculate organ dose is provided in ORAUT-OTIB-0006 (ORAUT 2019) in Table B-3 for the PA and LAT chest 1986 and later based on this period having proper collimation of the X-ray beam and an HVL of 4 mm. Table 3-7 provides the factors from Tables B-7 and B-8 of NCRP Report 102 (NCRP 1989) used to calculate skin dose for chest X-ray procedures.

Table 3-7. Skin calculation factors – PA and LAT chest for 2001 to May 15, 2019.

Factor	PA	LAT
Back Scatter Factor (BSF)[a]	1.42	1.42
Absorption Factor (AF)[b]	32.66	148.4
Average Percentage Depth Doses (ADD)[c]	19.3	9.325

a. BSF from NCRP 102, Table B.8, based on 4.0 mm HVL and 35 × 35 cm field size.
b. AF from NCRP 102, Table B.7, based on 4.0 mm HVL, 24 cm Tissue Thickness for PA and 34 cm Tissue Thickness for LAT.
c. ADD from NCRP 102, Table B.8, based on 4.0 mm HVL, 35 × 35 cm field size, 12 cm depth for PA and 17 cm depth for LAT.

Any records from Methodist Medical Center HealthWorks or other noncovered facility should not be included in the dose assessment because they would be considered offsite facilities (ORAUT 2017). Due to the downsizing of ETTP, the ETTP Medical Department was relocated to an area in the City of Oak Ridge by the close of business on May 20, 2019. The X-ray equipment was last used on May 15, 2019, and remained in Building K-1007; but was deemed inoperable (Newman 2019). After May 15, 2019, all X-rays are to be performed at the Methodist Medical Center in Oak Ridge (Newman 2019). Again, because this is a noncovered facility, these exams should not be included in the dose reconstruction process.

It appears that the same Bennett machine was used from 2001 through May, 2019 (Prater 2015a, p. 3). The reported technique factors for 2008 are 90 kVp and 5 mAs for the PA chest, and 100 kVp 13 mAs for the LAT chest (Osborne 2015, p. 50). Measurements and calculation of the HVL and entrance skin exposure are available for 2000 to 2008. The measured HVL was 4.0 mm Al for the PA chest. The measurements provided were based on various torso thickness. For the PA chest a thickness of 23 cm, 25 cm, 27 cm and 30 cm reading are provided. For the LAT, a thickness of 36 cm 39 cm and 42 cm dose readings are provided. For the PA chest, interpolation between the average readings for 23 cm readings and the 25 cm was used to reflect the 24 cm torso assumption. For the LAT, the 36 cm average from 2000 to 2008 was used. The incident air kerma for the PA and LAT chests, respectively, and converted to incident air kerma as described in ORAUT-OTIB-0006 (ORAUT 2019), Equation 7-1. Manual technique factors were used up to August 27, 2009, when a phototimer was installed for phototimed exposures. The manual technique factors described are assumed from the period 2001 to 2019. These data are listed in Table 3-8.

3.4 ORGAN DOSE CALCULATIONS

Organ doses for PFG, PA, and LAT chest X-rays were based on the method described in ORAUT-OTIB-0006 (ORAUT 2019) and dose conversion factors (DCFs) in ICRP Publication 34 (1982). ICRP (1982) provides tables of average absorbed dose (in milligrays) in selected organs for selected X-ray projections at 1-Gy entrance kerma (i.e., air kerma without backscatter) for selected projections and selected beam qualities (i.e., various HVLs). These tables list the basic DCFs for converting air kerma to organ dose

Table 3-8. X-ray equipment and incident air kerma values.

Period	X-ray machine	kVp (kV)	Assumed HVL (mm Al)	Image size	PA chest incident air kerma (cGy)	LAT chest incident air kerma (cGy)
April, 1945–1956	GE (PFG)	68[a]	2.5	4 × 5 in. or 70 mm	5.61[a]	Not applicable
October, 1944–1961	Westinghouse 200-mA	65[a]	2.0	14 × 17 in.	0.0482[b]	Not applicable
1962–1970	Westinghouse 300-mA	Not applicable	2.5[c]	14 × 17 in.	0.0260[c]	Not applicable
1971–1986	Westinghouse 300-mA	Not applicable	4.0[c]	14 × 17 in.	0.010[c]	0.030[c]
1987–2000	Bennett	Not applicable	4.0[c]	14 × 17 in.	0.022[c]	0.035[c]
2001–May 15, 2019	Bennett	90/100[d]	4.0[d]	14 × 17 in.	0.006[e]	0.020[e]

a. Source: Gupton et al. (1957, p.22). The incident air kerma provided is for stereo PFG views.
b. Incident air kerma was determined using NCRP (1989) Table B-3, average air kerma rates, and corrected to the SSD assumed per OTIB-0006, Table 3-1.
c. Source: Cardarelli (2000, p.86).
d. Source: Osborne (2015, pp. 50, 56, 62, 69, 76, 83, 89, 95, 101). Average of HVLs from 2000 to 2008.
e Source: Osborne (2015, pp. 50, 56, 62, 69, 76, 83, 89, 95, 101). Average of measured values from 2000 to 2008.

Substitute DCFs for organs that are listed in the Interactive RadioEpidemiological Program (IREP) but without unique DCFs in ICRP Publication 34 (1982) were selected as described in ORAUT-OTIB-0006 (ORAUT 2019) or are footnoted in the organ dose tables. Incident air kerma was obtained from Table 3-8.

The tissue at risk for chronic lymphocytic leukemia is the B-lymphocytes. The dose to the B-lymphocytes was determined using the method in ORAUT-RPRT-0064, *Medical Dose to the B-Lymphocytes* (ORAUT 2014b), site-specific information, and ICRP Publication 34 DCFs (ICRP 1982). Table 3-9 provides dose distributions and statistical parameters for input into IREP for determining dose to the B-lymphocytes.

Table 3-9. IREP dose distributions and statistical parameters for the dose to the B-lymphocytes.[a]

Projection and period	IREP distribution	Parameter 1	Parameter 2	Parameter 3
Stereo PFG 1945–1956	Weibull3	2.886863	1.546264	0.014839
PA chest 1944–1961	Weibull3	2.83221	0.010106	7.18521E–06
PA chest 1962–1970	Weibull3	2.917501	0.007230	1.46275E–05
PA chest 1971–1986	Weibull3	2.096637	0.002936	2.06219E–05
LAT chest 1971–1986	Weibull3	2.109742	0.004551	3.26222E–05
PA chest 1987–2000	Weibull3	2.107841	0.006496	1.31169E–05
LAT chest 1987–2000	Weibull3	2.107070	0.005318	2.57348E–05
PA chest 2001–May 2019	Weibull3	2.093713	0.001736	1.60106E–05
LAT chest 2001–May 2019	Weibull3	2.112819	0.003059	1.29533E–06

a. From Chalmers (2019).

Table 3-10 lists the organ doses for all periods. Skin doses for all skin areas were determined according to the method described in ORAUT-OTIB-0006 (ORAUT 2019) and listed in Tables 3-11 and 3-12.

3.5 UNCERTAINTY

It is assumed that K-25 followed the recommended standard practices implemented at other medical facilities. Therefore, the sources of uncertainty are assumed to be the same as the default given in ORAUT-OTIB-0006 (ORAUT 2019). Dose reconstructors should input the organ dose equivalent as the mean of a normal distribution with a standard deviation of ±30%.

3.6 ATTRIBUTIONS AND ANNOTATIONS

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

Table 3-10. Organ dose equivalent[a] per X-ray procedure for chest X-ray examinations, 1944 to May 15, 2019.

Organ	Projection	April 1945–1956 GE; PFG (rem)	October 1944–1961 Westinghouse 14 × 17 in. (rem)	1962–1970 Westinghouse 14 × 17 in. rem)	1971–1986 Westinghouse 14 × 17 in. (rem)	1987–2000 Bennett 14 × 17 in. (rem)	2001–May 2019 Bennett 14 × 17 in. (rem)
Thyroid	PA	9.76E–01[b]	7.28E–03[bc]	4.52E–03[b]	7.80E–04	1.72E–03	4.65E–04
Thyroid	LAT	Not applicable	Not applicable	Not applicable	4.92E–03	5.74E–03	3.27E–03
Eye/brain	PA	1.79E–01[c]	1.01–03[cd]	8.32E–04[c]	7.80E–04	1.72E–03	4.65E–04
Eye/brain	LAT	Not applicable	Not applicable	Not applicable	4.92E–03	5.74E–03	3.27E–03
Ovaries	PA	9.42E–01[d]	5.54E–03[ef]	4.37E–03	5.20E–05	1.14E–04	3.10E–05
Ovaries	LAT	Not applicable	Not applicable	Not applicable	7.50E–05	8.75E–05	4.99E–05
Urinary bladder/ prostate	PA	9.42E–01[d]	5.54E–03[ef]	4.37E–03	5.20E–05	1.14E–04	3.10E–05
Urinary bladder/ prostate	LAT	Not applicable	Not applicable	Not applicable	7.50E–05	8.75E–05	4.99E–05
Colon/rectum	PA	9.42E–01[d]	5.54E–03[ef]	4.37E–03	5.20E–05	1.14E–04	3.10E–05
Colon/rectum	LAT	Not applicable	Not applicable	Not applicable	7.50E–05	8.75E–05	4.99E–05
Testes	PA	5.10E–02[d]	2.75E–04[ef]	2.37E–04	1.00E–07	2.20E–07	5.96E–08
Testes	LAT	Not applicable	Not applicable	Not applicable	3.00E–06	3.50E–06	2.00E–06
Lung (male)	PA	2.35E+00	1.61E–02	1.09E–02	6.28E–03	1.38E–02	3.74E–03
Lung (male)	LAT	Not applicable	Not applicable	Not applicable	9.39E–03	1.10E–02	6.25E–03
Lung (female)	PA	2.53E+00	1.71E–02	1.17E–02	6.74E–03	1.48E–02	4.02E–03
Lung (female)	LAT	Not applicable	Not applicable	Not applicable	1.05E–02	1.23E–02	7.01E–03
Liver/gall bladder/spleen/ pancreas	PA	2.53E+00	1.71E–02	1.17E–02	6.74E–03	1.48E–02	4.02E–03
Liver/gall bladder/spleen/ pancreas	LAT	Not applicable	Not applicable	Not applicable	1.05E–02	1.23E–02	7.01E–03
Thymus	PA	2.53E+00	1.71E–02	1.17E–02	6.74E–03	1.48E–02	4.02E–03
Thymus	LAT	Not applicable	Not applicable	Not applicable	1.05E–02	1.23E–02	7.01E–03
Esophagus	PA	2.53E+00	1.71E–02	1.17E–02	6.74E–03	1.48E–02	4.02E–03
Esophagus	LAT	Not applicable	Not applicable	Not applicable	1.05E–02	1.23E–02	7.01E–03
Stomach	PA	2.53E+00	1.71E–02	1.17E–02	6.74E–03	1.48E–02	4.02E–03
Stomach	LAT	Not applicable	Not applicable	Not applicable	1.05E–02	1.23E–02	7.01E–03
Bone Surface	PA	2.53E+00	1.71E–02	1.17E–02	6.74E–03	1.48E–02	4.02E–03
Bone Surface	LAT	Not applicable	Not applicable	Not applicable	1.05E–02	1.23E–02	7.01E–03
Remainder	PA	2.53E+00	1.71E–02	1.17E–02	6.74E–03	1.48E–02	4.02E–03
Remainder	LAT	Not applicable	Not applicable	Not applicable	1.05E–02	1.23E–02	7.01E–03
Breast	PA	2.75E–01	1.54E–03	1.27E–03	1.16E–03	2.55E–03	6.92E–04
Breast	LAT	Not applicable	Not applicable	Not applicable	1.03E–02	1.20E–02	6.85E–03

Organ	Projection	April 1945–1956 GE; PFG (rem)	October 1944–1961 Westinghouse 14 × 17 in. (rem)	1962–1970 Westinghouse 14 × 17 in. rem)	1971–1986 Westinghouse 14 × 17 in. (rem)	1987–2000 Bennett 14 × 17 in. (rem)	2001–May 2019 Bennett 14 × 17 in. (rem)
Uterus	PA	8.36E–01[e]	4.96E–03[f]	3.87E–03	5.20E–05	1.14E–04	3.10E–05
Uterus	LAT	Not applicable	Not applicable	Not applicable	6.30E–05	7.35E–05	4.19E–05
Bone marrow (male)	PA	5.16E–01	3.33E–03	2.39E–03	1.78E–03	3.92E–03	1.06E–03
Bone marrow (male)	LAT	Not applicable	Not applicable	Not applicable	2.28E–03	2.66E–03	1.52E–03
Bone marrow (female)	PA	4.82E–01	3.04E–03	2.24E–03	1.72E–03	3.78E–03	1.03E–03
Bone marrow (female)	LAT	Not applicable	Not applicable	Not applicable	1.77E–03	2.07E–03	1.18E–03
Entrance skin	PA	6.62E+00[f]	6.36E–02[f]	3.51E–02[f]	1.42E–02[f]	3.12E–02[f]	8.47E–03
Entrance skin	LAT	Not applicable	Not applicable	Not applicable	4.26E–02[f]	4.97E–02[f]	2.83E–02

a. Dose conversion factors from Tables A.2 through A.9, ICRP (1982).
b. Dose conversion factor for anterior-posterior C-spine multiplied by depth dose correction factor of 0.20 as described in ORAUT-OTIB-0006 (2019).
c. Dose conversion factor for PA chest.
d. Dose conversion factor for PA Abdominal used.
e. Dose conversion factor for PA abdomen, because this organ is considered to be in the primary beam of a poorly collimated field.
f. Incident air kerma multiplied by a backscatter factor (NCRP 1989) of 1.18, 1.32, 1.35, or 1.42 for HVLs of 2.0, 2.5, and 4.0 mm Al, respectively.

Table 3-11. Skin dose guidance and skin dose equivalents for chest projections, October 1944 through 1970.[a,b]

Area of skin	PFG April 1945–1956 guidance	PFG April 1945–1956 dose (rem)	PA chest October 1944–1961 guidance	PA chest October 1944–1961 dose (rem)	PA chest 1962–1970 guidance	PA chest 1962–1970 dose (rem)
Right front shoulder	EXSD	1.44E–01	EXSD	1.21E–03	EXSD	7.65E–04
Right back shoulder	ENSD	6.62E+00	ENSD	6.36E–02	ENSD	3.51E–02
Left front shoulder	EXSD	1.44E–01	EXSD	1.21E–03	EXSD	7.65E–04
Left back shoulder	ENSD	6.62E+00	ENSD	6.36E–02	ENSD	3.51E–02
Right upper arm to elbow	10% ENSD	6.62E–01	ENSD	6.36E–02	ENSD	3.51E–02
Left upper arm to elbow	10% ENSD	6.62E–01	ENSD	6.36E–02	ENSD	3.51E–02
Left hand	ENSD	6.62E+00	ENSD	6.36E–02	ENSD	3.51E–02
Right hand	ENSD	6.62E+00	ENSD	6.36E–02	ENSD	3.51E–02
Left elbow, forearm, wrist	10% ENSD	6.62E–01	ENSD	6.36E–02	ENSD	3.51E–02
Right elbow, forearm, wrist	10% ENSD	6.62E–01	ENSD	6.36E–02	ENSD	3.51E–02
Right side of head (including ear and temple)	10% ENSD	6.62E–01	10% ENSD	6.36E–03	10% ENSD	3.51E–03
Left side of head (including ear and temple)	10% ENSD	6.62E–01	10% ENSD	6.36E–03	10% ENSD	3.51E–03
Front left thigh	RSD (0.52 m)	9.26E–04	RSD (0.52 m)	1.58E–05	RSD (0.52m)	1.01E–05
Back left thigh	RSD (0.52 m)	9.26E–04	RSD (0.52 m)	1.58E–05	RSD (0.52m)	1.01E–05
Front right thigh	RSD (0.52 m)	9.26E–04	RSD (0.52 m)	1.58E–05	RSD (0.52m)	1.01E–05
Back right thigh	RSD (0.52 m)	9.26E–04	RSD (0.52 m)	1.58E–05	RSD (0.52m)	1.01E–05
Left knee and below	RSD (0.86 m)	3.39E–04	RSD (0.86 m)	5.77E–06	RSD (0.86m)	3.68E–06
Right knee and below	RSD (0.86 m)	3.39E–04	RSD (0.86 m)	5.77E–06	RSD (0.86m)	3.68E–06
Left side of face	Eye/brain	1.79E–01	Eye/brain	1.01E–03	Eye/Brain	8.32E–04
Right side of face	Eye/brain	1.79E–01	Eye/brain	1.01E–03	Eye/Brain	8.32E–04
Left side of neck	10% ENSD	6.62E–01	ENSD	6.36E–02	ENSD	3.51E–02
Right side of neck	10% ENSD	6.62E–01	ENSD	6.36E–02	ENSD	3.51E–02
Back of head	10% ENSD	6.62E–01	10% ENSD	6.36E–03	10% ENSD	3.51E–03
Front of neck	Eye/brain	1.79E–01	Eye/brain	1.01E–03	Eye/Brain	8.32E–04
Back of neck	10% ENSD	6.62E–01	ENSD	6.36E–02	ENSD	3.51E–02
Front torso: base of neck to end of sternum	EXSD	1.44E–01	EXSD	1.21E–03	EXSD	8.32E–04
Front torso: end of sternum to lowest rib	EXSD	1.44E–01	EXSD	1.21E–03	EXSD	8.32E–04
Front torso: lowest rib to iliac crest	EXSD	1.44E–01	EXSD	1.21E–03	EXSD	8.32E–04
Front torso: iliac crest to pubis	10% EXSD	1.44E–02	10% EXSD	1.21E–04	10% EXSD	8.32E–05
Back torso: base of neck to mid–back	ENSD	6.62E+00	ENSD	6.36E–02	ENSD	3.51E–02
Back torso: mid–back to lowest rib	ENSD	6.62E+00	ENSD	6.36E–02	ENSD	3.51E–02
Back torso: lowest rib to iliac crest	ENSD	6.62E+00	ENSD	6.36E–02	ENSD	3.51E–02
Back torso: buttocks (Iliac crest and below)	10% ENSD	6.62E–01	10% ENSD	6.36E–03	10% ENSD	3.51E–03
Right torso: base of neck to end of sternum	ENSD	6.62E+00	ENSD	6.36E–02	ENSD	3.51E–02
Right torso: end of sternum to lowest rib	ENSD	6.62E+00	ENSD	6.36E–02	ENSD	3.51E–02
Right torso: lowest rib to iliac crest	ENSD	6.62E+00	ENSD	6.36E–02	ENSD	3.51E–02

Area of skin	PFG April 1945–1956 guidance	PFG April 1945–1956 dose (rem)	PA chest October 1944–1961 guidance	PA chest October 1944–1961 dose (rem)	PA chest 1962–1970 guidance	PA chest 1962–1970 dose (rem)
Right torso: iliac crest to pubis (right hip)	10% ENSD	6.62E–01	10% ENSD	6.36E–03	10% ENSD	3.51E–03
Left torso: base of neck to end of sternum	ENSD	6.62E+00	ENSD	6.36E–02	ENSD	3.51E–02
Left torso: end of sternum to lowest rib	ENSD	6.62E+00	ENSD	6.36E–02	ENSD	3.51E–02
Left torso: lowest rib to iliac crest	ENSD	6.62E+00	ENSD	6.36E–02	ENSD	3.51E–02
Left torso: iliac crest to pubis (left hip)	10% ENSD	6.62E–01	10% ENSD	6.36E–03	10% ENSD	3.51E–03

a. Values less than 0.1 mrem shown to one significant digit.
b. EXSD = exit skin dose; ENSD = entrance skin dose; RSD = remote skin dose.

Table 3-12. Skin dose guidance and skin dose equivalents for chest projections, 1971 to May 15, 2019.[a,b]

Area of skin	PA chest ≥1971 guidance	LAT chest ≥1971 guidance	1971–1986 PA chest dose (rem)	1971–1986 LAT chest dose (rem)	1987–2000 PA chest dose (rem)	1987–2000 LAT chest dose (rem)	2001–May 2019 PA chest dose (rem)	2001–May 2019 LAT chest dose (rem)
Right front shoulder	EXSD	ENSD	4.83E–04	4.26E–02	1.06E–03	4.97E–02	2.88E–04	2.83E–02
Right back shoulder	ENSD	ENSD	1.42E–02	4.26E–02	3.12E–02	4.97E–02	8.47E–03	2.83E–02
Left front shoulder	EXSD	EXSD	4.83E–04	3.19E–04	1.06E–03	3.72E–04	2.88E–04	2.12E–04
Left back shoulder	ENSD	EXSD	1.42E–02	3.19E–04	3.12E–02	3.72E–04	8.47E–03	2.12E–04
Right upper arm to elbow	10% ENSD	ENSD	1.42E–03	4.26E–02	3.12E–03	4.97E–02	8.47E–04	2.83E–02
Left upper arm to elbow	10% ENSD	EXSD	1.42E–03	3.19E–04	3.12E–03	3.72E–04	8.47E–04	2.12E–04
Left hand	10% ENSD	10% ENSD	1.42E–03	4.26E–03	3.12E–03	4.97E–03	8.47E–04	2.83E–03
Right hand	10% ENSD	10% ENSD	1.42E–03	4.26E–03	3.12E–03	4.97E–03	8.47E–04	2.83E–03
Left elbow, forearm, wrist	10% ENSD	10% ENSD	1.42E–03	4.26E–03	3.12E–03	4.97E–03	8.47E–04	2.83E–03
Right elbow, forearm, wrist	10% ENSD	10% ENSD	1.42E–03	4.26E–03	3.12E–03	4.97E–03	8.47E–04	2.83E–03
Right side of head (including ear and temple)	10% ENSD	10% ENSD	1.42E–03	4.26E–03	3.12E–03	4.97E–03	8.47E–04	2.83E–03
Left side of head (including ear and temple)	10% ENSD	10% ENSD	1.42E–03	4.26E–03	3.12E–03	4.97E–03	8.47E–04	2.83E–03
Front left thigh	RSD (0.52m)	RSD (0.52m)	5.57E–06	8.08E–06	1.23E–05	9.43E–06	3.32E–06	5.38E–06
Back left thigh	RSD (0.52m)	RSD (0.52m)	5.57E–06	8.08E–06	1.23E–05	9.43E–06	3.32E–06	5.38E–06
Front right thigh	RSD (0.52m)	RSD (0.52m)	5.57E–06	8.08E–06	1.23E–05	9.43E–06	3.32E–06	5.38E–06
Back right thigh	RSD (0.52m)	RSD (0.52m)	5.57E–06	8.08E–06	1.23E–05	9.43E–06	3.32E–06	5.38E–06
Left knee and below	RSD (0.86m)	RSD (0.86m)	2.04E–06	2.95E–06	4.48E–06	3.45E–06	1.22E–06	1.97E–06
Right knee and below	RSD (0.86m)	RSD (0.86m)	2.04E–06	2.95E–06	4.48E–06	3.45E–06	1.22E–06	1.97E–06
Left side of face	Eye/Brain	10% ENSD	7.80E–04	4.26E–03	1.72E–03	4.97E–03	4.65E–04	2.83E–03
Right side of face	Eye/Brain	10% ENSD	7.80E–04	4.26E–03	1.72E–03	4.97E–03	4.65E–04	2.83E–03
Left side of neck	10% ENSD	10% ENSD	1.42E–03	4.26E–03	3.12E–03	4.97E–03	8.47E–04	2.83E–03
Right side of neck	10% ENSD	10% ENSD	1.42E–03	4.26E–03	3.12E–03	4.97E–03	8.47E–04	2.83E–03
Back of head	10% ENSD	10% ENSD	1.42E–03	4.26E–03	3.12E–03	4.97E–03	8.47E–04	2.83E–03
Front of neck	Thyroid	10% ENSD	7.80E–04	4.26E–03	1.72E–03	4.97E–03	4.65E–04	2.83E–03
Back of neck	10% ENSD	10% ENSD	1.42E–03	4.26E–03	3.12E–03	4.97E–03	8.47E–04	2.83E–03
Front torso: base of neck to end of sternum	EXSD	Lung	4.83E–04	1.05E–02	1.06E–03	1.23E–02	2.88E–04	7.01E–03
Front torso: end of sternum to lowest rib	EXSD	Lung	4.83E–04	1.05E–02	1.06E–03	1.23E–02	2.88E–04	7.01E–03
Front torso: lowest rib to iliac crest	10% EXSD	10% Lung	4.83E–05	1.05E–03	1.06E–04	1.23E–03	2.88E–05	7.01E–04
Front torso: iliac crest to pubis	10% EXSD	10% Lung	4.83E–05	1.05E–03	1.06E–04	1.23E–03	2.88E–05	7.01E–04

Area of skin	PA chest ≥1971 guidance	LAT chest ≥1971 guidance	1971–1986 PA chest dose (rem)	1971–1986 LAT chest dose (rem)	1987–2000 PA chest dose (rem)	1987–2000 LAT chest dose (rem)	2001–May 2019 PA chest dose (rem)	2001–May 2019 LAT chest dose (rem)
Back torso: base of neck to mid–back	ENSD	Lung	1.42E–02	1.05E–02	3.12E–02	1.23E–02	8.47E–03	7.01E–03
Back torso: mid–back to lowest rib	ENSD	Lung	1.42E–02	1.05E–02	3.12E–02	1.23E–02	8.47E–03	7.01E–03
Back torso: lowest rib to iliac crest	10% ENSD	10% Lung	1.42E–03	1.05E–03	3.12E–03	1.23E–03	8.47E–04	7.01E–04
Back torso: buttocks (Iliac crest and below)	10% ENSD	10% Lung	1.42E–03	1.05E–03	3.12E–03	1.23E–03	8.47E–04	7.01E–04
Right torso: base of neck to end of sternum	ENSD	ENSD	1.42E–02	4.26E–02	3.12E–02	4.97E–02	8.47E–03	2.83E–02
Right torso: end of sternum to lowest rib	ENSD	ENSD	1.42E–02	4.26E–02	3.12E–02	4.97E–02	8.47E–03	2.83E–02
Right torso: lowest rib to iliac crest	10% ENSD	10% ENSD	1.42E–03	4.26E–03	3.12E–03	4.97E–03	8.47E–04	2.83E–03
Right torso: iliac crest to pubis (right hip)	10% ENSD	10% ENSD	1.42E–03	4.26E–03	3.12E–03	4.97E–03	8.47E–04	2.83E–03
Left torso: base of neck to end of sternum	ENSD	EXSD	1.42E–02	3.19E–04	3.12E–02	3.72E–04	8.47E–03	2.12E–04
Left torso: end of sternum to lowest rib	ENSD	EXSD	1.42E–02	3.19E–04	3.12E–02	3.72E–04	8.47E–03	2.12E–04
Left torso: lowest rib to iliac crest	10% ENSD	10% EXSD	1.42E–03	3.19E–05	3.12E–03	3.72E–05	8.47E–04	2.12E–05
Left torso: iliac crest to pubis (left hip)	10% ENSD	10% EXSD	1.42E–03	3.19E–05	3.12E–03	3.72E–05	8.47E–04	2.12E–05

a. Values less than 0.1 mrem shown to one significant digit.
b. EXSD = exit skin dose; ENSD = entrance skin dose; RSD = remote skin dose.

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GLOSSARY

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

collimation
Restriction of the size of an X-ray beam by various types of beam limiting devices. Collimation of the X-ray beam to the size of the image receptor (typically film) is considered good practice.

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 rad, rep, or grays.

dose conversion factor
The quotient of the organ absorbed dose or dose equivalent under specified conditions by the associated field quantity (e.g., air kerma or fluence).

filtration
Process of filtering an X-ray beam, usually with millimeter thicknesses of aluminum material between the X-ray source and the film, that preferentially absorbs photons from the beam. Usually measured in equivalent millimeters of aluminum. See *half-value layer*.

gaseous diffusion plant
Facility where uranium hexafluoride (UF_6) gas is filtered to enrich the ^{235}U and separate it from ^{238}U. The process requires enormous amounts of electric power and results in an increase in ^{235}U enrichment from 1% to about 3%.

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.

grid
Device that consists of a series of thin, closely spaced lead strips that is placed between the person being X-rayed and the X-ray film to reduce interaction of scattered radiation with the film.

half-value layer (HVL)
Thickness of a specified substance, usually specified in equivalent millimeters of aluminum, which, when introduced in the path of a given beam of radiation, reduces 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.

kilovoltage (kVp)
Electrical potential difference in units of kilovolts between the cathode and the anode in an X ray generating tube. See *technique*.

lateral (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.

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 the Energy Employees Occupational Illness Compensation Program Act of 2000.

photofluorography (PFG)
Historical radiographic technique to produce 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.

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. The opposite of *view*.

radiograph
Static images produced on radiographic film by gamma rays or X-rays after passing through matter. In the context of the Energy Employees Occupational Illness Compensation Program Act of 2000, radiographs are X-ray images of the various parts of the body used to screen for disease.

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

standard error
The standard deviation of the sampling distribution of a statistic. For example, the standard error of the sample mean of n observations is sigma/sqrt(n), where sigma is the standard deviation of the original observations.

stereoscopic
Noting or pertaining to simulated three-dimensional viewing of photographic or radiographic images with two views of the same image taken at slightly different angles.

technique
Combination of X-ray machine settings (technique factors) used to produce radiographs, which consists of the kilovoltage, tube current (milliamperes), and exposure time (seconds). The last

two parameters are often multiplied to yield the electric charge that has crossed the X-ray tube during the exposure in units of milliampere-seconds. Any combination of time and tube current that produces a given product in milliampere-seconds produces the same exposure for a fixed peak kilovoltage. Also called technic.

uncertainty

Standard deviation of the mean of a set of measurements. The standard error reduces to the standard deviation of the measurement when there is only one determination. See *error*. Also called standard error.

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.