Los Alamos National Laboratory – Occupational Medical Dose	ORAUT-TKBS-0010-3	Rev. 02
	Effective Date:	01/10/2023
	Supersedes:	Revision 01

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PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
12/29/2004	00	Technical basis document for the Los Alamos National Laboratory – Occupational Medical Dose. Incorporates comments from internal and NIOSH reviews. First approved issue. Initiated by Jack E. Buddenbaum.
09/14/2010	01	Revised to incorporate data captured since the last revision to better document what has come to be known about PFG at LANL, and to add skin doses for all projections and periods. Added references and included Attributions and Annotations Section. Incorporates formal internal and NIOSH review comments. Constitutes a total rewrite of the document. Training required: As determined by the Objective Manager. Initiated by Donald N. Stewart.
01/10/2023	02	Revised to remove X-ray doses and to reference ORAUT-OTIB-0006 in their place. Site-specific X-ray doses recalculated. Recalculated uncertainty using 24-cm torso thickness. This revision results in a change in the assigned doses. Incorporates formal internal and NIOSH review comments. Constitutes a total rewrite of the document. Initiated by John M. Byrne and authored by JoAnn M. Jenkins.

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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
ERDA	U.S. Energy Research and Development Administration
EXSD	exit skin dose
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	kilovolts-peak
LANL	Los Alamos National Laboratory
LASL	Los Alamos Scientific Laboratory
LAT	lateral
m	meter
mA	milliampere
mAs	milliampere-second
mGy	milligray
mm	millimeter
mrem	millirem
NCRP	National Council on Radiation Protection and Measurements
NIOSH	National Institute for Occupational Safety and Health
ORAU	Oak Ridge Associated Universities
ORAUT	ORAU Team
PA	posterior-anterior
PFG	photofluorograph
RaLa	radioactive lanthanum
RSD	remote skin dose
s	second
SEC	Special Exposure Cohort
SSD	source-to-skin distance

SRDB Ref ID	Site Research Database Reference Identification (number)
TA	technical area
TBD	technical basis document
U.S.C.	*United States Code*
§	section or sections

3.1 INTRODUCTION

Technical basis documents (TBDs) and site profile documents are not official determinations made by the National Institute for Occupational Safety and Health (NIOSH) but are rather general working documents that provide historical background information and guidance to assist in the preparation of dose reconstructions at particular U.S. 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), such as changing scientific understanding of operations, processes, or procedures involving radioactive materials. These documents may be used to assist NIOSH staff in the evaluation of Special Exposure Cohort (SEC) petitions and the completion of individual dose reconstructions under Part B of the Energy Employees Occupational Illness Compensation Program Act of 2000 (EEOICPA).

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 term "AWE facility" is defined in EEOICPA to mean "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 *United States Code* (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—(A) 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 (B) with regard to which the [DOE] has or had—(i) a proprietary interest; or (ii) 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 DOE determines whether a site meets the statutory definition of an AWE facility and the U.S. Department of Labor (DOL) determines if a site is a DOE facility and, if it is, designates it as such.

Under EEOICPA, a Part B cancer 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., a "covered employee with cancer"). After DOL determines that a claim meets the eligibility requirements under Part B of 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. 42 U.S.C. § 7384l(11). Also under EEOICPA, the types of exposure to be included in dose reconstructions for DOE employees are those radiation exposures incurred in the performance of duty. As such, NIOSH includes all radiation exposures received as a condition of employment at DOE facilities in its dose reconstructions for covered employees, which may include radiation exposures related to the Naval Nuclear Propulsion Program at DOE facilities, if applicable. This is because NIOSH does not determine the fraction of total measured radiation exposure at a DOE facility that is contributed by the Naval Nuclear Propulsion Program at the DOE facility during a specified period of time 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 2010a]:

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

3.1.1 Purpose

The purpose of this TBD is to describe the occupational medical X-ray screening program and practices at Los Alamos National Laboratory (LANL). Dose reconstructors will use this information as needed to assign medical X-ray doses to workers at LANL.

3.1.2 Scope

LANL had an occupational health program starting in 1949. The purpose of the program was to medically screen new personnel, perform termination physicals, discover disease, and periodically examine workers exposed to hazards [Hempelman 1946; Shipman 1950a; Los Alamos Scientific Laboratory (LASL) 1951, p. 13]. These medical examinations typically included chest X-rays [LASL 1948]. The doses from these radiographic procedures depended not only on the characteristics of the X-ray machine and the procedures used, but also on the frequency of the examinations. This TBD describes the technical aspects of X-ray dose from screening X-rays administered before employment and periodically thereafter as a condition of employment at LANL.

3.1.3 Special Exposure Cohort

The Secretary of the U.S. Department of Health and Human Services has designated four classes of LANL employees as additions to the SEC based on the findings and recommendations of NIOSH and the Advisory Board on Radiation and Worker Health Board.

September 1, 1944, through July 18, 1963, Radioactive Lanthanum

> *Employees of the Department of Energy predecessor agencies and their contractors or subcontractors who were monitored or should have been monitored for exposure to ionizing radiation associated with radioactive lanthanum (RaLa) operations at Technical Area 10 (Bayo Canyon Site), Technical Area 35 (Ten Site), and Buildings H, Sigma, and U (located within Technical Area 1) at the Los Alamos National Laboratory (LANL) for a number of work days aggregating at least 250 work days during the period from September 1, 1944 through July 18, 1963, or in combination with work days within the parameters established for one or more other classes of employees in the SEC* [Leavitt 2006].

NIOSH determined later that it could not limit the class to the specified RaLa operations and areas, and the Secretary designated a second class that encompasses the first [NIOSH 2006].

March 15, 1943, through December 31, 1975

> *Employees of DOE, its predecessor agencies, or DOE contractors or subcontractors who were monitored or should have been monitored for radiological exposures while working in operational TAs with a history of radioactive material use at LANL for a number of work days aggregating at least 250 work days from March 15, 1943, through December 31, 1975, or in combination with work days within the parameters established for one or more other classes of employees in the SEC* [Leavitt 2007].

Through the course of ongoing dose reconstruction and research, NIOSH determined that, due to undocumented worker movements across the site and limited worker-specific information pertaining to work locations, it was unable to eliminate any specific worker from potential exposure scenarios based on assigned work location. NIOSH has found that a determination cannot always be made as to whether or not an employee worked in TAs with a history of radioactive material use, or if an employee should have been monitored for radiological exposures. Accordingly, NIOSH determined that it was necessary to remove the area-specific and monitoring criteria from the class description above, and to expand the SEC class definition to include all areas of LANL, and all employees of the

DOE, its predecessor agencies, and their contractors and subcontractors who worked at LANL during the specified period, regardless of monitoring. For this reason, the classes of employees listed below were added, which encompass both previous classes [NIOSH 2006, 2007].

March 15, 1943, through December 31, 1975

> *All employees of the Department of Energy, its predecessor agencies, and their contractors and subcontractors who worked at the Los Alamos National Laboratory in Los Alamos, New Mexico from March 15, 1943 through December 31, 1975, for a number of work days aggregating at least 250 work days, occurring either solely under this employment or in combination with work days within the parameters established for one or more other classes of employees in the Special Exposure Cohort* [Sebelius 2010].

January 1, 1976, through December 31, 1995

> *All employees of the Department of Energy, its predecessor agencies, and their contractors and subcontractors who worked at the Los Alamos National Laboratory (LANL) in Los Alamos, New Mexico from January 1, 1976, through December 31, 1995, for a number of work days aggregating at least 250 work days, occurring either solely under this employment or in combination with work days within the parameters established for one or more other classes of employees in the Special Exposure Cohort.* [Sebelius 2012].

NIOSH has determined that it does not have access to sufficient information – including internal personnel dosimetry, workplace monitoring data, or sufficient process and radiological source information – that would allow it to estimate with sufficient accuracy the potential internal doses workers might have received during the above periods. NIOSH has determined that there is insufficient information either to estimate the maximum radiation dose for every type of cancer for which radiation doses are reconstructed that could have been incurred under plausible circumstances by any member of the classes or to estimate the radiation doses of members of the classes more precisely than a maximum dose estimate [NIOSH 2010b, 2012].

Although NIOSH found that it is not possible to completely reconstruct radiation doses for the proposed class, NIOSH intends to use any internal and external monitoring data that may become available for an individual claim (and that can be interpreted using existing NIOSH dose reconstruction processes or procedures). Therefore, dose reconstructions for individuals employed at LANL during the period from March 15, 1943 through December 31, 1995, but who do not qualify for inclusion in the SEC, may be performed using these data as appropriate NIOSH [2010b, 2012].

From an occupational external dose reconstruction perspective, partial dose reconstructions can include, and are limited to, external dose from gamma emitters from 1946 onward, dose from beta emitters from 1949 onward, and neutron dose from 1946 onward.

NIOSH finds that adequate reconstruction of medical dose is likely feasible using claimant-favorable assumptions in ORAUT-OTIB-0006, *Dose Reconstruction from Occupational Medical X-Ray Procedures* (OTIB-0006; Oak Ridge Associated Universities [ORAU] Team [ORAUT] 2019), as well as LANL technical basis documents, collectively referred to as ORAUT-TKBS-0010 [NIOSH 2010b, 2012].

3.2 EXAMINATION FREQUENCIES

Table 3-1 lists frequencies of chest X-rays through the years for specific groups of workers. From 1943 through 1976, workers received preemployment and termination chest X-rays. Hempelman recommended annual chest X-rays for workers exposed to radiation and every 6 months for workers handling uranium, plutonium, polonium, and beryllium oxide [Hempelman 1944, p. 5]. In addition, because of their exposure to silica flour and ground glass, workers in the glass-blowing shop were to be X-rayed every 6 months [Grier and Hardy 1949–1950, p. 5].

Table 3-1. Default frequency of occupational chest X-rays.

Period	Workers	Chest projections	Frequency
1943–1956	All workers	Single-projection PFG[a,b]	Preemployment Termination
1943–1956	Workers handling uranium, plutonium, polonium, or beryllium oxide; glass blowers[c,d]	Single-projection PFG[a,b]	Semiannual
1943–1956	Workers exposed to radiation[c]	Single-projection PFG[a,b]	Annual
1957–1976	All workers[c]	PA	Preemployment Every 3 years Termination
1977–2001	Workers handling asbestos or beryllium; workers >45 years old[e,f]	PA and LAT[g,h]	Annual
1977–2001	All other workers <45 years old[f]	PA and LAT[g,h]	Biennial
2002–present	Workers monitored for exposure to beryllium, asbestos, silica or cadmium; high-altitude workers; Nano-2 and tower climber workers[i]	PA and LAT[j,k]	Baseline at entry into monitoring program
2002–present	Beryllium, silica[l] and asbestos workers 18-35 years old; asbestos and silica[l] workers of any age that have been exposed to asbestos/silica[l] <10 years; high-altitude workers ≤40 years old[i]	PA and LAT[j,k]	(l)
2002–present	Asbestos or silica workers 36-45 years old who have worked with asbestos/silica ≥10 years; high-altitude workers >40 years old[i]	PA and LAT[j,l]	Every 2 years
2002–present	Asbestos or silica workers >46 years old who have worked with asbestos/silica for ≥10 years; cadmium workers[j]	PA and LAT[i,j,k]	Annual
2002–present	Tower climbers[i]	PA and LAT[j,k]	Exit of program

a. Shipman [1955].
b. Shipman [1958].
c. Hempelman [1944].
d. Grier and Hardy [1949].
e. Voelz et al. [1981].
f. ERDA [1975].
g. Haynie and Gutierrez [1978].
h. Gutierrez and Haynie [1977].
i. Romero [2022].
j. Martinez [2021].
k. Butler [2022].
l. Every 5 years, except silica workers: every 5 years through September 2021, every 3 years after.

Shipman states that photofluorographs (PFGs) were used unless factors dictated that 14- by 17-in. film would be better [Shipman 1955, p. 23]. Several historical monthly progress reports document the number of PFG and 14- by 17-in. films performed by the occupational medical service and, in almost all cases, the number of PFGs exceeded the number of 14- by 17-in. films in a given period, indicating the common use of this imaging technique at LANL [Shipman 1949, 1950b, 1955; LASL 1949, p. 19].

It appears that both the PFGs and the 14- by 17-in. chest films consisted of a single posterior-anterior (PA) projection in the earliest period [Shipman 1949]. Dose reconstructors should be able to identify the PFG examinations in the claim file records when a “film number” is recorded on the X-ray record. The film number indicates the use of roll film (rather than sheet film) commonly used in the PFG camera apparatus. Use of PFGs at LANL ended in 1956 [Shipman 1958, p. 35].

Shipman writes that the periodic examinations were done every 3 years unless conditions indicated otherwise [Shipman 1958, p. 34]. Starting in about 1977, two chest projections (PA and lateral [LAT]) were being performed routinely for screening [Gutierrez and Haynie 1977; Haynie and Gutierrez 1978]. No more information is available for the X-ray screening frequency after the late 1970s, although documents [e.g., LASL 1979] refer to being in compliance with Chapter 0528 of the U.S. Energy Research and Development Administration (ERDA) Contractor Occupational Medical Program manual, which required annual X-ray screening for workers more than 45 years old and biennial X-ray screening for workers less than 45 years old [ERDA 1975]. In 2002, when the Food and Drug Administration performed a survey of the X-ray equipment, the survey questionnaire indicated that LANL was no longer routinely performing chest X-ray screening on workers [Antonsen 1998]. From 2002 to the present, LANL only performed chest X-rays on employees enrolled in the surveillance programs listed in Table 3-1 [Martinez 2021, Romero 2022]. The frequency of examinations is dependent upon the surveillance program which the employee was enrolled and the employee’s age.

Two historical documents mention the existence of mammography equipment [Valentine 1989, p. 95] and mammography screening [Wade 1991, p. 16]. Mammography screening was likely offered to employees as a convenience to them. Mammography would not have been used to screen for occupational disease. For this reason, and because mammography screening is commonplace in the general population and the risk from exposure to mammography screening is assumed to be included in the risk models of the Interactive RadioEpidemiological Program (IREP), dose from mammography is not included as part of occupational medical dose in this TBD [NIOSH 2002].

LANL medical records, including X-ray records, are available from LANL on special request. The records state if the X-ray was “routine” (i.e., screening, sometimes abbreviated “Rt”), or “special” (i.e., diagnostic – not screening). The records also provide the worker’s employer at LANL (Zia, ERDA, U.S. Atomic Energy Commission, University of California, etc.). Refer to Section 3.4.1 for guidance in assigning X-ray doses.

3.3 EQUIPMENT AND TECHNIQUES

Organ doses from occupational medical X-rays at LANL are presented for all types of X-ray equipment employed over the operational period. The types of X-ray equipment used are listed in Table 3-2. Tables 3-3 and 3-4 list the specific technique factors reported by LANL along with measured or estimated beam qualities for the different machines. Table 3-4 includes the half-value layers (HVLs) that were used to select the dose conversion factors (DCFs) for dose calculation.

Table 3-2. X-ray equipment.[a]

Technique	Period	Equipment
PFG	1943–1956	Unknown, 70-mm fluororoentgenogram, single exposure. Default values from OTIB-0006 for one nonstereo exposure should be used for this period.
Type I(a)	1943–1970	Unknown. Default values for 14- by 17–in. radiographic chest from OTIB-0006 should be used for this period.
Type I(b)	1971–1975	Unknown. Default values for 14- by 17–in. radiographic chest from OTIB-0006 should be used for this period.
Type II	1976–1984	General Electric KX810; 3.75-mm total filtration should be assumed for this period.
Type III	1985–1994	General Electric DXD 350II Control, Single-Phase Generator, Auto Collimator, 12:1 Grid, 3.5-mm Al equivalent total filtration. Kodak X-Omatic 90-s cold-water processor, 400-speed film-screen system, Kodak Lanex cassettes-rare earth. Fuji Ortho G film [Antonsen 1998; Shalkowski et al. 1991].
Type IV[b]	1995–2002	General Electric DXD 350II Control, Single-Phase Generator, Auto Collimator, 12:1 Grid, 3.5-mm Al equivalent total filtration. Kodak X-Omatic 90-s cold-water processor, 400-speed film-screen system, Kodak Lanex cassettes-rare earth. Fuji Ortho G film [Antonsen 1998].
Type V	2003–2014[c]	Quantum Medical Imaging Cosmos 22 Control, High Frequency Generator, Varian X-ray tube, Heustis medical collimator. 2.5-mm Al equivalent total filtration. CXDI22 Canon sensor-digital camera [Velarde 2009].
Type VI[c]	2015–2020	Quantum Model QG-6500, Odyssey HF Series Three Phase Generator, 2.5-mm Al equivalent total filtration [Martinez 2021].
Type VII[c]	2021–present	Del Medical Model FMT18M Digital Unit, 1.5-mm Al equivalent total filtration [Martinez 2021].

a. OTIB-0006 = Oak Ridge Associated Universities (ORAU) Team (ORAUT) [2019].
b. Type IV equipment same as Type III, different technique factors used.
c. Source: Martinez [2021].

Table 3-3. Technique factors used for each type of X-ray equipment.

Machine		Projection[a]	Current (mA)	Voltage (kVp)	Exposure time (s)
Type I(a)	1943–1970	Unknown	Unknown	Unknown	Unknown
Type I(b)	1971–1975	Unknown	Unknown	Unknown	Unknown
Type II	1976–1984[b]	PA chest	300	90	1/30
Type III	1985–1994[c]	PA chest	200	102	1/30
Type IV	1995–2002[d]	PA chest	200	114	1/50
Type V	2003–2014[e]	PA chest	200	104	1/30
Type VI	2015–2020[e]	PA chest	800	80	1/125
Type VII	2021–present[e]	PA chest	3.2 (mAs)	120	Not applicable

a. The average PA chest measures 24 cm; the average LAT chest measures 36 cm.
b. Source: Gutierrez and Haynie [1976].
c. Source: Shalkowski et al. [1991].
d. Source: Antonsen [1998].
e. Source: Martinez [2021].

Table 3-4. HVLs (mm) used to determine DCFs for dose calculations.[a]

Machine type	Periods of use	Total filtration [Al equiv.] (reported or estimated)	HVL based on filtration and kVp[b]	HVL used for DCF selection[c]
PFG	1943–1956	Unknown (2.5)[d]	2.5	2.5
Type I[a]	1943–1970	Unknown (2.5)[d]	2.5	2.5
Type I[b]	1971–1975	Unknown (2.5)[d]	2.5	2.5
Type II	1976–1984[e]	3.75	3.3 at 90 kVp	3.5
Type III	1985–1994[f]	3.5	3.4 at 100 kVp	3.5
Type IV	1995–2002[g]	3.5	3.7 at 110 kVp	4.0
Type V	2003–2014[h]	2.5	3.4	3.5
Type VI	2015–2020[h]	2.5	2.5	2.5
Type VII	2021–present[h]	1.5	1.5	1.5

a. ICRP = International Commission on Radiological Protection; NCRP = National Council on Radiation Protection and Measurements.
b. [NCRP 1989].
c. [ICRP 1982].
d. Source: Based on OTIB-0006.
e. Source: Gutierrez and Haynie [1976].
f. Source: Shalkowski et al. [1991].
g. Source: Antonsen [1998].
h. Source: Martinez [2021].

As mentioned above, PFGs were performed from 1943 to 1956 [Shipman 1955, 1958]. During this time, chest X-rays were also performed on 14- by 17-in. film [Shipman 1954], but nothing is known about this equipment except that it was probably in the hospital [Shipman 1952]. The first mention of a specific brand and model of X-ray equipment is in Gutierrez and Haynie [1976]. The General Electric X-ray machine is mentioned, along with the technical information from a survey of that machine in the new occupational medical building. Even though Gutierrez and Haynie show a possible total filtration of 6.75-mm Al equivalent resulting from the summation of the individual component filtration equivalents, it seems doubtful that this much filtration was actually used for the following reasons:

- To obtain the possible total of 6.75-mm Al eq., the equivalent filtration of the collimator and the removable filters were added together. Removable filters (placed in a slot) were usually used with a cone-type beam-limiting device because such a device did not have any inherent filtration. However, an adjustable collimator does have some inherent filtration. Apparently, an adjustable light-localizing collimator was added to this machine [Gutierrez and Haynie 1976], making removable filters unnecessary. When the thickness of the removable filters is left out of the summation, the total is about 3.75-mm Al eq., which is a much more reasonable amount.

- It is extremely doubtful that a radiologist would have accepted radiographs produced with 6.75-mm Al filtration. With that much filtration, there would have been little differential absorption in tissue and little contrast in the image.

For these reasons, the total filtration for this period is assumed to be 3.75-mm Al eq., which results in an HVL of 3.3-mm Al at 90 kVp.

Another General Electric machine, the DXD 350II, was installed in 1985 and used until approximately 2003 [Antonsen 1998]. In 2003, a Quantum Medical Imaging Odyssey X-ray machine was installed [Velarde 2009]. It was replaced with a Quantum Model QG-6500, Odyssey HF Series Three Phase Generator in 2015. In 2021, a Del Medical Model FMT18M Digital Unit was installed [Martinez 2021].

3.4 ORGAN DOSES

This section presents X-ray organ doses for occupational X-rays at LANL for all types of equipment and all periods.

Dose values for PFGs at LANL are based on the default values for PFGs in OTIB-0006, except that the doses are calculated for single-exposure PFGs (not stereo exposures). The PFG doses in OTIB-0006 are divided by 2 to obtain single-exposure PFG doses. Dose reconstructors should be able to identify the PFGs in the claim file records when the examination occurred between 1943 and 1956 and when a “film number” is recorded; the latter indicates the use of roll rather than sheet film. Dose reconstructors should assume a two-exposure stereo PFG only when the words “serial 1 and 2” appear on the record or radiologist’s interpretation.

Dose values for conventional 14- by 17-in. chest radiography for LANL from 1943 to 1975 are also based on the default values for chest radiography in OTIB-0006.

Organ Dose
Dose values for the remaining periods, with the exception of 1985 to 1994 and 2015 to 2020, were calculated using average air kerma rates from Figure A-1 of the International Commission on Radiological Protection (ICRP) Publication 34 [ICRP 1982] in units of mGy/mAs at 100 cm. The data in Figure A-1 were corrected to a source-to-skin distance (SSD) of 154 cm and for the actual voltage, current, and phase of the machines for the various periods. An example calculation is shown below:

$$K_{a,i(\text{1976-1984})} = K_{a,i(\text{ICRP34})} \times Current \times ExposureTime \times \left(\frac{100}{154}\right)^2 \times 0.1\,\text{cGy/mGy} \qquad (3\text{-}1)$$

where

$K_{a,i(\text{1976-1984})}$	=	incident air kerma in air (cGy)
$K_{a,i(\text{ICRP34})}$	=	incident air kerma in air from ICRP Publication 34 (mGy/mAs)
Current	=	mA
Exposure Time	=	s

Therefore

$$\begin{aligned} K_{a,i(\text{1976-1984})} &= 0.045\,\text{mGy/mAs} \times 300\,\text{mA} \times 0.0333\,\text{s} \times \left(\frac{100}{154}\right)^2 \times 0.1\,\text{cGy/mGy} \\ &= 0.01897\ \text{cGy} \end{aligned} \qquad (3\text{-}2)$$

where

$K_{a,i(\text{1976-1984})}$ = incident air kerma in air for 1976 to 1984 (cGy)

For the period 1985 to 1994 the actual measured air kerma rate was used [Olsher 1991]. A conversion factor from the Quantum X-ray machine was used to calculate air kerma for the 2015 to 2020 period [Martinez 2021]. For both PA and LAT chest projections, a standard source-to-image distance of 72 in. (183 cm) was assumed for all periods. In accordance with OTIB-0006, entrance air kerma in air from the LAT chest projection is estimated at 2.5 times more than the PA entrance kerma. It was assumed that all the X-ray machines were single-phase except the high-frequency Type V, VI, and VII units. The values for the high-frequency units from Figure A-1 were multiplied by a factor of 1.8 [ICRP 1982]. ICRP Publication 34 [ICRP 1982] contains tables of average absorbed dose (milligray) in selected organs for selected X-ray projections at 1-Gy entrance kerma (i.e., air kerma without backscatter) and selected beam qualities (i.e., various HVLs). The organ doses were calculated by multiplying the ICRP organ DCFs by the entrance air kerma in air. The resulting organ doses for all machines and periods are listed in Table 3-5 [ORAUT 2022a].

Skin Dose

Skin doses were calculated using the method described in OTIB-0006. Table 3-6 lists the skin dose guidance for various areas of skin for various projections. Table 3-7 lists skin doses from all machines and periods calculated according to the guidance [ORAUT 2022a].

Doses were generally determined by analogy with anatomical location for organs not listed in ICRP Publication 34 [ICRP 1982] but specified in IREP in accordance with the guidance in OTIB-0006.

Chronic Lymphocytic Leukemia

The tissues at risk for chronic lymphocytic leukemia are 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 2014], site-specific information, and ICRP Publication 34 DCFs [ICRP 1982]. Dose values for the B-lymphocytes for conventional 14- by 17-in. chest radiography for LANL from 1943 to 1975 are based on the values in OTIB-0006. Dose values for the B-lymphocytes for PFGs for LANL from 1943 to 1956 are based on the values in ORAUT-RPRT-0064. Table 3-8 provides dose distributions and statistical parameters for input into IREP for determining dose to the B-lymphocytes.

Table 3-5. Organ dose equivalents (rem) for chest projections, all periods.[a]

PA

Organ	PFG 1943–1956[b]	1943–1970[c]	1971–1975[c]	1976–1984	1985–1994	1995–2002	2003–2014	2015–08/2021	09/2021–present
Thyroid	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	1.18E-03	1.36E-03	9.36E-04	2.64E-03	5.32E-04	2.98E-04
Eye/brain	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	1.18E-03	1.36E-03	9.36E-04	2.64E-03	5.32E-04	2.98E-04
Ovaries	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	6.08E-05	7.04E-05	6.24E-05	1.36E-04	1.66E-05	5.42E-06
Urinary/bladder	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	6.08E-05	7.04E-05	6.24E-05	1.36E-04	1.66E-05	5.42E-06
Colon/rectum	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	6.08E-05	7.04E-05	6.24E-05	1.36E-04	1.66E-05	5.42E-06
Testes	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	1.90E-07	2.20E-07	1.20E-07	4.25E-07	1.66E-07	2.71E-07
Lung (male)	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	1.07E-02	1.24E-02	7.54E-03	2.40E-02	6.97E-03	6.58E-03
Lung (female)	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	1.16E-02	1.34E-02	8.09E-03	2.59E-02	7.50E-03	6.77E-03
Thymus	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	1.16E-02	1.34E-02	8.09E-03	2.59E-02	7.50E-03	6.77E-03
Esophagus	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	1.16E-02	1.34E-02	8.09E-03	2.59E-02	7.50E-03	6.77E-03
Stomach	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	1.16E-02	1.34E-02	8.09E-03	2.59E-02	7.50E-03	6.77E-03
Bone surface	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	1.16E-02	1.34E-02	8.09E-03	2.59E-02	7.50E-03	6.77E-03
Liver/gall bladder/ spleen	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	1.16E-02	1.34E-02	8.09E-03	2.59E-02	7.50E-03	6.77E-03
Remainder organs	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	1.16E-02	1.34E-02	8.09E-03	2.59E-02	7.50E-03	6.77E-03
Breast	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	1.73E-03	2.00E-03	1.39E-03	3.87E-03	8.15E-04	4.88E-04
Uterus	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	5.70E-05	6.60E-05	6.24E-05	1.28E-04	2.16E-05	8.13E-06
Bone marrow (male)	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	2.77E-03	3.21E-03	2.14E-03	6.21E-03	1.53E-03	1.33E-03
Bone marrow (female)	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	2.68E-03	3.10E-03	2.06E-03	5.99E-03	1.43E-03	1.17E-03
ENSD[d]	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	2.66E-02	3.08E-02	1.70E-02	5.95E-02	2.25E-02	3.47E-02

LAT

Organ	PFG 1943–1956[b]	1943–1970[c]	1971–1975[c]	1976–1984	1985–1994	1995–2002	2003–2014	2015–08/2021	09/2021–present
Thyroid	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	7.17E-03	8.31E-03	4.92E-03	1.60E-02	4.78E-03	4.67E-03
Eye/brain	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	7.17E-03	8.31E-03	4.92E-03	1.60E-02	4.78E-03	4.67E-03
Ovaries	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	7.60E-05	8.80E-05	7.50E-05	1.70E-04	2.50E-05	6.77E-06
Urinary/bladder	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	7.60E-05	8.80E-05	7.50E-05	1.70E-04	2.50E-05	6.77E-06
Colon/rectum	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	7.60E-05	8.80E-05	7.50E-05	1.70E-04	2.50E-05	6.77E-06
Testes	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	4.75E-06	5.50E-06	3.00E-06	1.06E-05	4.16E-06	6.77E-06
Lung (male)	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	1.31E-02	1.52E-02	9.39E-03	2.93E-02	8.03E-03	6.91E-03
Lung (female)	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	1.47E-02	1.71E-02	1.05E-02	3.29E-02	9.15E-03	7.79E-03
Thymus	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	1.47E-02	1.71E-02	1.05E-02	3.29E-02	9.15E-03	7.79E-03

Organ	PFG 1943–1956[b]	1943–1970[c]	1971–1975[c]	1976–1984	1985–1994	1995–2002	2003–2014	2015–08/2021	09/2021–present
Esophagus	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	1.47E-02	1.71E-02	1.05E-02	3.29E-02	9.15E-03	7.79E-03
Stomach	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	1.47E-02	1.71E-02	1.05E-02	3.29E-02	9.15E-03	7.79E-03
Bone surface	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	1.47E-02	1.71E-02	1.05E-02	3.29E-02	9.15E-03	7.79E-03
Liver/gall bladder/ spleen	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	1.47E-02	1.71E-02	1.05E-02	3.29E-02	9.15E-03	7.79E-03
Remainder organs	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	1.47E-02	1.71E-02	1.05E-02	3.29E-02	9.15E-03	7.79E-03
Breast	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	1.50E-02	1.74E-02	1.03E-02	3.36E-02	1.06E-02	1.30E-02
Uterus	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	6.65E-05	7.70E-05	6.30E-05	1.49E-04	2.50E-05	6.77E-06
Bone marrow (male)	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	2.90E-03	3.36E-03	2.28E-03	6.48E-03	1.54E-03	1.35E-03
Bone marrow (female)	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	2.28E-03	2.64E-03	1.77E-03	5.10E-03	1.21E-03	9.48E-04
ENSD[d]	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	6.65E-02	7.70E-02	4.26E-02	1.49E-01	5.62E-02	9.48E-02

a. Source: ORAUT [2022a].
b. See OTIB-0006 and apply 50% because LANL did not typically perform stereo PFGs.
c. See OTIB-0006 and apply 100% before 1976.
d. ENSD = entrance skin dose. ENSD is determined by multiplying the entrance air kerma in air by the backscatter factors of 1.28, 1.35, 1.40, and 1.42 for HVL of 1.5-mm Al, 2.5-mm, 3.0- or 4.0-mm Al, respectively, from NCRP Report 102 [NCRP 1989, Table B-8]. Skin doses for all areas of skin are provided in Table 3-7.

Table 3-6. Skin dose guidance for chest projections, all periods.[a]

Area of skin	PFG	PA through 1970	PA after 1970	LAT after 1970
Right front shoulder	EXSD	EXSD	EXSD	ENSD
Right back shoulder	ENSD	ENSD	ENSD	ENSD
Left front shoulder	EXSD	EXSD	EXSD	EXSD
Left back shoulder	ENSD	ENSD	ENSD	EXSD
Right upper arm to elbow	10% ENSD	ENSD	10% ENSD	ENSD
Left upper arm to elbow	10% ENSD	ENSD	10% ENSD	EXSD
Left hand	ENSD	ENSD	10% ENSD	10% ENSD
Right hand	ENSD	ENSD	10% ENSD	10% ENSD
Left elbow, forearm, wrist	10% ENSD	ENSD	10% ENSD	10% ENSD
Right elbow, forearm, wrist	10% ENSD	ENSD	10% ENSD	10% ENSD
Right side of head (including ear and temple)	10% ENSD	10% ENSD	10% ENSD	10% ENSD
Left side of head (including ear and temple)	10% ENSD	10% ENSD	10% ENSD	10% ENSD
Front left thigh	RSD (0.52 m)	RSD (0.52 m)	RSD (0.52 m)	RSD (0.52 m)
Back left thigh	RSD (0.52 m)	RSD (0.52 m)	RSD (0.52 m)	RSD (0.52 m)
Front right thigh	RSD (0.52 m)	RSD (0.52 m)	RSD (0.52 m)	RSD (0.52 m)
Back right thigh	RSD (0.52 m)	RSD (0.52 m)	RSD (0.52 m)	RSD (0.52 m)
Left knee and below	RSD (0.86 m)	RSD (0.86 m)	RSD (0.86 m)	RSD (0.86 m)

Area of skin	PFG	PA through 1970	PA after 1970	LAT after 1970
Right knee and below	RSD (0.86 m)	RSD (0.86 m)	RSD (0.86 m)	RSD (0.86 m)
Left side of face	Eye/brain	Eye/brain	Eye/brain	10% ENSD
Right side of face	Eye/brain	Eye/brain	Eye/brain	10% ENSD
Left side of neck	10% ENSD	ENSD	10% ENSD	10% ENSD
Right side of neck	10% ENSD	ENSD	10% ENSD	10% ENSD
Back of head	10% ENSD	10% ENSD	10% ENSD	10% ENSD
Front of neck	Eye/brain	Eye/brain	Thyroid	10% ENSD
Back of neck	10% ENSD	ENSD	10% ENSD	10% ENSD
Front torso: base of neck to end of sternum	EXSD	EXSD	EXSD	Lung
Front torso: end of sternum to lowest rib	EXSD	EXSD	EXSD	Lung
Front torso: lowest rib to iliac crest	EXSD	EXSD	10% EXSD	10% lung
Front torso: iliac crest to pubis	10% EXSD	10% EXSD	10% EXSD	10% lung
Back torso: base of neck to mid-back	ENSD	ENSD	ENSD	Lung
Back torso: mid-back to lowest rib	ENSD	ENSD	ENSD	Lung
Back torso: lowest rib to iliac crest	ENSD	ENSD	10% ENSD	10% lung
Back torso: buttocks (Iliac crest and below)	10% ENSD	10% ENSD	10% ENSD	10% lung
Right torso: base of neck to end of sternum	ENSD	ENSD	ENSD	ENSD
Right torso: end of sternum to lowest rib	ENSD	ENSD	ENSD	ENSD
Right torso: lowest rib to iliac crest	ENSD	ENSD	10% ENSD	10% ENSD
Right torso: iliac crest to pubis (right hip)	10% ENSD	10% ENSD	10% ENSD	10% ENSD
Left torso: base of neck to end of sternum	ENSD	ENSD	ENSD	EXSD
Left torso: end of sternum to lowest rib	ENSD	ENSD	ENSD	EXSD
Left torso: lowest rib to iliac crest	ENSD	ENSD	10% ENSD	10% EXSD
Left torso: iliac crest to pubis (left hip)	10% ENSD	10% ENSD	10% ENSD	10% EXSD

a. EXSD = exit skin dose; RSD = remote skin dose.

Table 3-7. Skin dose (rem) from chest projections, 1943 to present.

	PA								
Area of skin	PFG 1943–1956[a]	1943–1970[b]	1971–1975[b]	1976–1984[c]	1985–1994[c]	1995–2002[c]	2003–2014[c]	2015–08/2021[c]	09/2021–present[c]
Right front shoulder	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	7.75E-04	8.98E-04	5.78E-04	1.73E-03	4.76E-04	2.67E-04
Right back shoulder	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	2.66E-02	3.08E-02	1.70E-02	5.95E-02	2.25E-02	3.47E-02
Left front shoulder	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	7.75E-04	8.98E-04	5.78E-04	1.73E-03	4.76E-04	2.67E-04
Left back shoulder	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	2.66E-02	3.08E-02	1.70E-02	5.95E-02	2.25E-02	3.47E-02
Right upper arm to elbow	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	2.66E-03	3.08E-03	1.70E-03	5.95E-03	2.25E-03	3.47E-03
Left upper arm to elbow	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	2.66E-03	3.08E-03	1.70E-03	5.95E-03	2.25E-03	3.47E-03
Left hand	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	2.66E-03	3.08E-03	1.70E-03	5.95E-03	2.25E-03	3.47E-03
Right hand	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	2.66E-03	3.08E-03	1.70E-03	5.95E-03	2.25E-03	3.47E-03

Area of skin	PFG 1943–1956[a]	1943–1970[b]	1971–1975[b]	1976–1984[c]	1985–1994[c]	1995–2002[c]	2003–2014[c]	2015–08/2021[c]	09/2021–present[c]
Left elbow, forearm, wrist	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	2.66E-03	3.08E-03	1.70E-03	5.95E-03	2.25E-03	3.47E-03
Right elbow, forearm, wrist	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	2.66E-03	3.08E-03	1.70E-03	5.95E-03	2.25E-03	3.47E-03
Right side of head including ear and temple	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	2.66E-03	3.08E-03	1.70E-03	5.95E-03	2.25E-03	3.47E-03
Left side of head including ear and temple	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	2.66E-03	3.08E-03	1.70E-03	5.95E-03	2.25E-03	3.47E-03
Front left thigh	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	9.55E-06	1.11E-05	6.67E-06	2.14E-05	6.45E-06	5.15E-06
Back left thigh	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	9.55E-06	1.11E-05	6.67E-06	2.14E-05	6.45E-06	5.15E-06
Front right thigh	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	9.55E-06	1.11E-05	6.67E-06	2.14E-05	6.45E-06	5.15E-06
Back right thigh	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	9.55E-06	1.11E-05	6.67E-06	2.14E-05	6.45E-06	5.15E-06
Left knee and below	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	3.49E-06	4.04E-06	2.44E-06	7.81E-06	2.36E-06	1.88E-06
Right knee and below	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	3.49E-06	4.04E-06	2.44E-06	7.81E-06	2.36E-06	1.88E-06
Left side of face	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	1.18E-03	1.36E-03	9.36E-04	2.64E-03	5.32E-04	2.98E-04
Right side of face	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	1.18E-03	1.36E-03	9.36E-04	2.64E-03	5.32E-04	2.98E-04
Left side of neck	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	2.66E-03	3.08E-03	1.70E-03	5.95E-03	2.25E-03	3.47E-03
Right side of neck	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	2.66E-03	3.08E-03	1.70E-03	5.95E-03	2.25E-03	3.47E-03
Back of head	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	2.66E-03	3.08E-03	1.70E-03	5.95E-03	2.25E-03	3.47E-03
Front of neck	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	1.18E-03	1.36E-03	9.36E-04	2.64E-03	5.32E-04	2.98E-04
Back of neck	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	2.66E-03	3.08E-03	1.70E-03	5.95E-03	2.25E-03	3.47E-03
Front torso: base of neck to end of sternum	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	7.75E-04	8.98E-04	5.78E-04	1.73E-03	4.76E-04	2.67E-04
Front torso: end of sternum to lowest rib	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	7.75E-04	8.98E-04	5.78E-04	1.73E-03	4.76E-04	2.67E-04
Front torso: lowest rib to iliac crest	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	7.75E-05	8.98E-05	5.78E-05	1.73E-04	4.76E-05	2.67E-05
Front torso: iliac crest to pubis	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	7.75E-05	8.98E-05	5.78E-05	1.73E-04	4.76E-05	2.67E-05
Back torso: base of neck to mid–back	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	2.66E-02	3.08E-02	1.70E-02	5.95E-02	2.25E-02	3.47E-02
Back torso: mid–back to lowest rib	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	2.66E-02	3.08E-02	1.70E-02	5.95E-02	2.25E-02	3.47E-02
Back torso: lowest rib to iliac crest	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	2.66E-03	3.08E-03	1.70E-03	5.95E-03	2.25E-03	3.47E-03
Back torso: buttocks (Iliac crest and below)	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	2.66E-03	3.08E-03	1.70E-03	5.95E-03	2.25E-03	3.47E-03
Right torso: base of neck to end of sternum	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	2.66E-02	3.08E-02	1.70E-02	5.95E-02	2.25E-02	3.47E-02
Right torso: end of sternum to lowest rib	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	2.66E-02	3.08E-02	1.70E-02	5.95E-02	2.25E-02	3.47E-02

Area of skin	PFG 1943–1956[a]	1943–1970[b]	1971–1975[b]	1976–1984[c]	1985–1994[c]	1995–2002[c]	2003–2014[c]	2015–08/2021[c]	09/2021–present[c]
Right torso: lowest rib to iliac crest	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	2.66E-03	3.08E-03	1.70E-03	5.95E-03	2.25E-03	3.47E-03
Right torso: iliac crest to pubis (right hip)	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	2.66E-03	3.08E-03	1.70E-03	5.95E-03	2.25E-03	3.47E-03
Left torso: base of neck to end of sternum	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	2.66E-02	3.08E-02	1.70E-02	5.95E-02	2.25E-02	3.47E-02
Left torso: end of sternum to lowest rib	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	2.66E-02	3.08E-02	1.70E-02	5.95E-02	2.25E-02	3.47E-02
Left torso: lowest rib to iliac crest	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	2.66E-03	3.08E-03	1.70E-03	5.95E-03	2.25E-03	3.47E-03
Left torso: iliac crest to pubis (left hip)	50% OTIB-0006	100% OTIB-0006	100% OTIB-0006	2.66E-03	3.08E-03	1.70E-03	5.95E-03	2.25E-03	3.47E-03

LAT

Area of skin	1976–1984[c]	1985–1994[c]	1995–2002[c]	2003–2014[c]	2015–08/2021[c]	09/2021–present[c]
Right front shoulder	6.65E-02	7.70E-02	4.26E-02	1.49E-01	5.62E-02	9.48E-02
Right back shoulder	6.65E-02	7.70E-02	4.26E-02	1.49E-01	5.62E-02	9.48E-02
Left front shoulder	4.08E-04	4.73E-04	3.19E-04	9.13E-04	2.46E-04	1.04E-04
Left back shoulder	4.08E-04	4.73E-04	3.19E-04	9.13E-04	2.46E-04	1.04E-04
Right upper arm to elbow	6.65E-02	7.70E-02	4.26E-02	1.49E-01	5.62E-02	9.48E-02
Left upper arm to elbow	4.08E-04	4.73E-04	3.19E-04	9.13E-04	2.46E-04	1.04E-04
Left hand	6.65E-03	7.70E-03	4.26E-03	1.49E-02	5.62E-03	9.48E-03
Right hand	6.65E-03	7.70E-03	4.26E-03	1.49E-02	5.62E-03	9.48E-03
Left elbow, forearm, wrist	6.65E-03	7.70E-03	4.26E-03	1.49E-02	5.62E-03	9.48E-03
Right elbow, forearm, wrist	6.65E-03	7.70E-03	4.26E-03	1.49E-02	5.62E-03	9.48E-03
Right side of head including ear and temple	6.65E-03	7.70E-03	4.26E-03	1.49E-02	5.62E-03	9.48E-03
Left side of head including ear and temple	6.65E-03	7.70E-03	4.26E-03	1.49E-02	5.62E-03	9.48E-03
Front left thigh	1.14E-05	1.32E-05	8.08E-06	2.55E-05	7.56E-06	5.83E-06
Back left thigh	1.14E-05	1.32E-05	8.08E-06	2.55E-05	7.56E-06	5.83E-06
Front right thigh	1.14E-05	1.32E-05	8.08E-06	2.55E-05	7.56E-06	5.83E-06
Back right thigh	1.14E-05	1.32E-05	8.08E-06	2.55E-05	7.56E-06	5.83E-06
Left knee and below	4.16E-06	4.82E-06	2.95E-06	9.31E-06	2.76E-06	2.13E-06
Right knee and below	4.16E-06	4.82E-06	2.95E-06	9.31E-06	2.76E-06	2.13E-06
Left side of face	6.65E-03	7.70E-03	4.26E-03	1.49E-02	5.62E-03	9.48E-03
Right side of face	6.65E-03	7.70E-03	4.26E-03	1.49E-02	5.62E-03	9.48E-03
Left side of neck	6.65E-03	7.70E-03	4.26E-03	1.49E-02	5.62E-03	9.48E-03
Right side of neck	6.65E-03	7.70E-03	4.26E-03	1.49E-02	5.62E-03	9.48E-03
Back of head	6.65E-03	7.70E-03	4.26E-03	1.49E-02	5.62E-03	9.48E-03
Front of neck	6.65E-03	7.70E-03	4.26E-03	1.49E-02	5.62E-03	9.48E-03
Back of neck	6.65E-03	7.70E-03	4.26E-03	1.49E-02	5.62E-03	9.48E-03

Area of skin	1976–1984[c]	1985–1994[c]	1995–2002[c]	2003–2014[c]	2015–08/2021[c]	09/2021–present[c]
Front torso: base of neck to end of sternum	1.47E-02	1.71E-02	1.05E-02	3.29E-02	9.15E-03	7.79E-03
Front torso: end of sternum to lowest rib	1.47E-02	1.71E-02	1.05E-02	3.29E-02	9.15E-03	7.79E-03
Front torso: lowest rib to iliac crest	1.47E-03	1.71E-03	1.05E-03	3.29E-03	9.15E-04	7.79E-04
Front torso: iliac crest to pubis	1.47E-03	1.71E-03	1.05E-03	3.29E-03	9.15E-04	7.79E-04
Back torso: base of neck to mid–back	1.47E-02	1.71E-02	1.05E-02	3.29E-02	9.15E-03	7.79E-03
Back torso: mid–back to lowest rib	1.47E-02	1.71E-02	1.05E-02	3.29E-02	9.15E-03	7.79E-03
Back torso: lowest rib to iliac crest	1.47E-03	1.71E-03	1.05E-03	3.29E-03	9.15E-04	7.79E-04
Back torso: buttocks (Iliac crest and below)	1.47E-03	1.71E-03	1.05E-03	3.29E-03	9.15E-04	7.79E-04
Right torso: base of neck to end of sternum	6.65E-02	7.70E-02	4.26E-02	1.49E-01	5.62E-02	9.48E-02
Right torso: end of sternum to lowest rib	6.65E-02	7.70E-02	4.26E-02	1.49E-01	5.62E-02	9.48E-02
Right torso: lowest rib to iliac crest	6.65E-03	7.70E-03	4.26E-03	1.49E-02	5.62E-03	9.48E-03
Right torso: iliac crest to pubis (right hip)	6.65E-03	7.70E-03	4.26E-03	1.49E-02	5.62E-03	9.48E-03
Left torso: base of neck to end of sternum	4.08E-04	4.73E-04	3.19E-04	9.13E-04	2.46E-04	1.04E-04
Left torso: end of sternum to lowest rib	4.08E-04	4.73E-04	3.19E-04	9.13E-04	2.46E-04	1.04E-04
Left torso: lowest rib to iliac crest	4.08E-05	4.73E-05	3.19E-05	9.13E-05	2.46E-05	1.04E-05
Left torso: iliac crest to pubis (left hip)	4.08E-05	4.73E-05	3.19E-05	9.13E-05	2.46E-05	1.04E-05

a. See OTIB-0006 and apply 50% because LANL did not typically perform stereo PFGs.
b. See OTIB-0006 and apply 100% before 1976.
c. Source: ORAUT [2022a].

Table 3-8. 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
PFG 1943–1956	Use ORAUT 2014	Use ORAUT 2014	Use ORAUT 2014	Use ORAUT 2014
PA 1943–1970	Use OTIB-0006	Use OTIB-0006	Use OTIB-0006	Use OTIB-0006
LAT 1943–1970	Use OTIB-0006	Use OTIB-0006	Use OTIB-0006	Use OTIB-0006
PA 1971–1975	Use OTIB-0006	Use OTIB-0006	Use OTIB-0006	Use OTIB-0006
LAT 1971–1975	Use OTIB-0006	Use OTIB-0006	Use OTIB-0006	Use OTIB-0006
PA 1976–1984	Weibull3	2.074754	0.004981	1.78162E-05
LAT 1976–1984	Weibull3	2.105124	0.006356	9.87032E-06
PA 1985–1994	Weibull3	2.049242	0.005697	7.05969E-05
LAT 1985–1994	Weibull3	2.082033	0.007364	2.67307E-06
PA 1995–2002	Weibull3	2.115078	0.00352	1.92489E-05
LAT 1995–2002	Weibull	2.120687	0.00459	N/A
PA 2003–2014	Weibull3	2.105327	0.0113	7.82527E-06
LAT 2003–2014	Weibull3	2.086014	0.014163	3.20232E-05
PA 2015–2020	Weibull	2.060644	0.003235	N/A
LAT 2015–2020	Lognormal	0.002992614[b]	1.717928149[b]	N/A
PA 2021–present	Weibull	2.045486	0.002831	N/A
LAT 2021–present	Weibull3	2.061269	0.003303	1.18406E-05

a. Source: ORAUT [2022b]; N/A = not applicable.
b. For the Lognormal 3 and Lognormal 2 distributions, the geometric mean and geometric standard deviation are calculated by exponentiating μ and σ, respectively (GM = exp(μ), GSD = exp(σ)) [ORAUT 2022b].

3.4.1 Dose Reconstruction Guidance

The information given below summarizes instructions given to the dose reconstructors in determining organ doses from occupational medical X-ray procedures. For the purpose of evaluating probability of causation, X-ray doses are always considered acute and to reflect photons with energies in the range from 30 to 250 keV. X-ray doses are assigned in IREP with a normal distribution in IREP Parameter 1 and the product of the organ dose multiplied by an uncertainty of 0.3 in Parameter 2 for the purpose of calculating probability of causation [ORAUT 2017].

3.4.1.1 Maximizing Approach

To maximize X-ray dose before 1957, assign X-rays based on the frequency in Table 3-1. If there is evidence of more frequent X-rays in the energy employee's medical record, those X-rays should be assigned. After 1956, assign annual X-rays for all years of employment. If there is evidence of more frequent X-rays in the energy employee's medical record, those X-rays should be assigned. Refer to OTIB-0006 for PFG and PA chest X-ray examination doses before 1976 [ORAUT 2019] and to Tables 3-5 and 3-7 for such doses after 1975. Refer to OTIB-0006 for examination doses for examinations other than PA chest X-rays if found in the worker's records and determined to be occupational in nature.

3.4.1.2 Best-Estimate Approach

Assign X-rays based on the actual X-ray records provided by the site. LANL provides all employee X-ray records in the medical record. Therefore, if no X-rays are provided in the medical record, it is likely the employee did not receive any X-rays. If no medical records are provided in the DOE or DOL record, request the medical records from the site to confirm that the employee did not receive any X-rays. If no medical records are received, following the request, the dose reconstructor should assume no X-ray exams were performed and no X-rays should be assigned. Refer to OTIB-0006 for PFG and PA chest X-ray examination doses before 1976 [ORAUT 2019] and to Tables 3-5 and 3-7 for such doses after 1976. Refer to OTIB-0006 for examination doses for examinations other than PA chest X-rays if found in the worker's records and determined to be occupational in nature.

3.5 UNCERTAINTY

Although many factors can introduce uncertainty and error into X-ray dose estimates, five factors contribute the most: measurement error (±2%), variation in peak kilovoltage (±9%), variation in beam current (±5%), variation in exposure time (±25%), and distance from the worker to the source of the X-rays (SSD) (±10%) [ORAUT 2019]. Other variables, such as the use of screens and grids, reciprocity failure, and film speed and development, do not affect the beam output intensity [OTIB-0006].

A reasonable approach is to assume that the uncertainties are in fact random and therefore to compute the combined statistical uncertainty as the square root of the sum of the squares of all the uncertainties: $(2^2 + 9^2 + 5^2 + 25^2 + 10^2)^{1/2}$, which equals ±28.9%. Rounding this up to ±30% provides an adequate and suitably conservative indication of uncertainty. Therefore, for a derived dose equivalent to an individual organ, a total combined standard uncertainty of ±30% can be assumed. Dose reconstructors should, therefore, input the organ dose equivalent as the mean of a normal distribution, with a standard uncertainty of ±30%.

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GLOSSARY

air kerma in air
The sum of kinetic energy of all charged particles liberated per unit mass of air. The unit is the joule per kilogram and is given the special name gray.

beam quality
Empirical measure of the ability of a polyenergetic X-ray beam to penetrate matter affected by the kilovoltage, anode material, voltage waveform, and filtration of an X-ray tube. The half-value layer in millimeters of aluminum is a typical measure of X-ray beam quality for the energy range used in radiography. Also called beam hardness. See *filtration*.

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 *beam quality* and *half-value layer*.

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 rad. Gray is also the plural.

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*.

Interactive RadioEpidemiological Program (IREP)
Computer program that uses a person's calculated annual organ doses and other information (e.g., gender, age at diagnosis, and age at exposure) to calculate the probability of causation of a specific cancer from a given pattern and level of radiation exposure.

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

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

organ dose
Dose to a given organ from a radiation exposure.

photofluorography
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. Photofluorography was the primary method of screening large populations for tuberculosis before the advent of nonradiographic screening methods. Also called fluorography or mass miniature radiography. Not to be confused with *fluoroscopy*.

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

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

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 joule per kilogram) of absorbing tissue. The rad has been replaced by the gray in the International System of Units (100 rad = 1 gray). The word derives from radiation absorbed dose; rad is also the plural.

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. See *radiology*.

radiology
Medical science and specialty of producing images on radiographic film or other media, which are used to identify, diagnose, and or treat diseases, injuries, or other conditions.

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.

screen
Fluorescent material in X-ray film cassettes that absorbs X-rays and converts them into light to expose the X-ray film. Also called intensifying screens.

source-to-image distance
Distance from the X-ray machine target (anode) to the plane of the image receptor (film). This distance is standardized for typical radiographic procedures. Chest X-rays, for example, are performed at a 72-inch source-to-image distance.

source-to-skin distance (SSD)
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.

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.

termination X-ray

X-ray, usually of the chest, taken when an employee separates from the company.

tube current

Average electrical current measured in milliamperes flowing from the cathode to the anode of an X-ray tube during operation of the tube.

X-ray

See *radiograph*.

X-ray tube

Evacuated electronic tube in which electrons are accelerated by an applied voltage to strike an anode or target and produce X-rays.