DOE Review Release 09/26/2024

Savannah River Site – Occupational Medical Dose

ORAUT-TKBS-0003-3 Rev. 06
Effective Date: 09/12/2024
Supersedes: Revision 05

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☐ New ☐ Total Rewrite ☒ Revision

PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
07/15/2003	00	First Approved Issue. Incorporates formal internal and NIOSH review comments. Initiated by Edward D. Scalsky.
08/21/2003	01	Approved issue of Revision 01. Incorporates formal internal and NIOSH review comments. Initiated by Edward D. Scalsky.
10/29/2004	02	Approved issue of Revision 02. Revised to incorporate medical X-ray changes and added section on photofluorography. Incorporates formal internal and NIOSH review comments. Initiated by Edward D. Scalsky.
04/05/2005	03	Approved issue of Revision 03. Incorporates formal internal and NIOSH review comments. Initiated by Edward D. Scalsky.
11/30/2009	04	Approved revision to separate the site profile into an Introduction and five TBDs. This revision is updated with newly acquired captured information. Includes Attributions and Annotations section. Specific changes are as follows: Added specific technique factors for PA and LAT projections for Type I machines and for LAT projections for Types II through IV machines in Table 3-3. Added Table 3-4. Rearranged the various sections and changed section headings: Section 3.3.1 changed from X-ray Apparatus to Photofluorography; Section 3.3.2 from Collimation to Radiography; Moved the existing Section 3.4.2 on Collimation to Section 3.4. Added Section 3.3.3. Replaced the text in the existing Section 3.5 that contained example calculations of doses for the various projection types with two paragraphs of new text describing how doses were assigned. The original Table B.2 is now Table 3-9. All organ doses for the period 1950-1970 for Type I X-ray equipment have decreased; also doses for the male lungs and female bone marrow have been added. Entrance air kerma and skin doses for the PA and LAT projections have been deleted from Table 3-9. Table 3-10 and Table 3-11 have been added. The discussion regarding the four potential sources of uncertainty has been deleted except for the final statement to assume a +30% uncertainty at the 99% confidence level as stated in OTIB-0006. Changed reported range on technique factors for the Picker machine. Values added to Table 3-3; The calculated entrance and exit skin doses were compared to the measured entrance and exit skin doses of Cooley (Cooley 1967) made on the mobile Picker machine for the PA chest for the 1950-1970 time period. The comparison is shown in Table 3-7. The 21% uncertainty derived from the Cooley measurements is substituted into the root mean square calculation for combined uncertainty instead of the 10% value initially reported from this source of uncertainty in ORAUT-OTIB-0006. As a result of this substitution, the resulting combined, standard uncertainty is 34%, and rounded up to 35%. Skin doses were put into a different table format to more closely match the skin dose tools. Incorporates formal internal and NIOSH review comments. Constitutes a total rewrite of the document. Training required: As determined by the Objective Manager. Initiated by Edward D. Scalsky and Elyse M. Thomas.

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
03/05/2024	05	Revised to address inconsistencies with latest version of ORAUT-OTIB-0006. Added Special Exposure Cohort information in Section 3.1.3. Updated with information through 2023. Updated tables and dose reconstruction guidance. Incorporates formal internal and NIOSH review comments. Constitutes a total rewrite of the document. Training required: As determined by the Objective Manager. Initiated by John M. Byrne and authored by JoAnn M. Jenkins.
09/12/2024	06	Revised to update all PA X-ray skin dose values for 1950-1970, except “Left torso: iliac crest to pubis (left hip)”, all PA X-ray skin dose values for 1971-July 1985, except “Right Shoulder, Front & Back”, and “Left torso: iliac crest to pubis (left hip)”, and only PA X-ray skin dose value for “Left torso: iliac crest to pubis (left hip)” for October 2014-present. Revisions located in Section 3.4. Incorporates formal internal and NIOSH review comments. Initiated by Wade C. Morris and authored by JoAnn M. Jenkins. Training required: As determined by the Objective Manager. Initiated by Wade C. Morris and authored by JoAnn M. Jenkins.

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ACRONYMS AND ABBREVIATIONS

ABRWH	Advisory Board on Radiation and Worker Health
AWE	Atomic Weapons Employer
cGy	centigray
cm	centimeter
CMX	Corrosion Mock-up Experiment
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
EXSD	exit skin dose
f	ratio of lens focal length to aperture
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
LAT	lateral
m	meter
mA	milliampere
mAs	milliampere-second
mGy	milligray
mm	millimeter
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	photofluorography
R	roentgen
RSD	remote skin dose
s	second
SEC	Special Exposure Cohort
SID	source-to-image distance
SRDB Ref ID	Site Research Database Reference Identification (number)

SRS	Savannah River Site
SSD	source-to-skin distance
TBD	technical basis document
TNX	Semi-works Laboratory
U.S.C.	*United States Code*
yr	year
§	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 2010]:

- 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 dose workers might have received at the Savannah River Site (SRS; formerly the Savannah River Plant). Occupational medical dose results from X-ray procedures performed for health screening of workers during preemployment and annual physical examinations. X-rays taken as a result of on- or off-the-job injuries are not eligible for inclusion in dose reconstruction under EEOICPA. This TBD contains the technical information that the Oak Ridge Associated Universities (ORAU) Team (ORAUT) will use to evaluate the doses.

3.1.2 Scope

SRS required preemployment and annual physical examinations as part of the occupational health and safety program. These medical examinations, which were performed to screen for disease and required as a condition of employment typically included chest X-rays. Radiation dose from these X-ray procedures depended on the characteristics of the X-ray machine, the number and type of projections for each type of procedure, and the frequency of the examinations or procedures. The X-ray techniques and equipment changed over the years and are presented and discussed in Sections 3.2 and 3.3. Section 3.4 presents organ dose tables and supporting documentation to assist dose reconstructors in evaluating occupational doses from these X-ray examinations. Section 3.5 discusses the uncertainty in the calculated doses.

3.1.3 Special Exposure Cohort

January 1, 1953, through September 30, 1972
The Secretary of the U.S. Department of Health and Human Services has added the following class of SRS employees to the SEC [Sebelius 2012, p. 3]:

> *All employees of the Department of Energy, its predecessor agencies, and their contractors and subcontractors who worked at the Savannah River Site from January 1, 1953, through September 30, 1972, 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 included in the Special Exposure Cohort.*

The Secretary based this designation on the findings of NIOSH's SEC evaluation report, which found it is not feasible to estimate internal exposures with sufficient accuracy for all externally monitored employees from January 1, 1953, through December 31, 1957, whose records have dosimetry codes A, G, CMX, or TNX. Further, NIOSH found that it lacked sufficient internal thorium monitoring data or other data or methods to support bounding internal thorium doses for SRS workers who might have worked with thorium in the 700 Area or the Corrosion Mock-up Experiment (CMX) and Semi-works Laboratory (TNX) areas from January 1, 1958, through September 30, 1972, whose records have dosimetry codes 5A, 5C, 6B through 6Z, 12D through 12H, or 12J through 12Z [NIOSH 2011].

October 1, 1972, through December 31, 1990
The Secretary has also added the following class [Becerra 2021, p. 3]:

> *All construction trade employees of Department of Energy subcontractors [excluding employees of the following prime contractors who worked at the Savannah River Site in Aiken, South Carolina, during the specified time periods: E. I. du Pont de Nemours and Company, October 1, 1972, through March 31, 1989; and Westinghouse Savannah River Company, April 1, 1989, through December 31, 1990], who worked at the Savannah River Site from October 1, 1972, through December 31, 1990, 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 included in the Special Exposure Cohort.

The Secretary based this designation on the recommendation of the Advisory Board on Radiation and Worker Health (ABRWH), which found that dose reconstruction for unmonitored subcontractor construction trade workers who should have been monitored via the permit-driven job-specific monitoring program is not feasible using the co-exposure models NIOSH developed due to the nature of radiological work assigned to transient subcontractor construction trades workers, the lack of assurance provided their bioassay monitoring, and identified gaps in the permit-driven job-specific monitoring program. The ABRWH concluded that the completeness and representation of subcontractors who were, or should have been, monitored has not been sufficiently established [Anderson 2021].

Although the ABRWH found that it is not possible to completely reconstruct radiation doses for either class, NIOSH intends to use any internal and external monitoring data that might become available for an individual claim and that can be interpreted using existing NIOSH dose reconstruction processes or procedures to conduct partial dose reconstructions for employees who do not qualify for inclusion in the SEC [NIOSH 2011; Anderson 2021].

3.2 EXAMINATION FREQUENCIES

SRS provided the information on the frequency of the X-ray screening examinations in Table 3-1 [Brown 2002, 2022, 2023; SRNS 2019a,b, 2020a,b, 2021]. X-ray frequency was determined by the age of the worker and the type of work. NIOSH informed DOE headquarters that it was not necessary to search for occupational X-rays performed as a condition of employment. Therefore, not all the claimant records from SRS contain all X-ray records [Brown 2002]. However, SRS will provide the records upon special request if necessary to determine the probability of causation. Dose reconstructors should assign dose using the appropriate frequencies in Table 3-1 unless the X-ray records were requested. In that case, include all X-rays performed for screening listed in the worker file to reconstruct occupational medical dose.

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

1950 to 1988

Frequency	Comment	Projections
Annually	All employees	PA chest
Annually	Construction and asbestos workers	PA and LAT chest

1989 to 1993

Frequency	Comment	Projections
Annually	Employees 50 yr old and older	PA chest
Biennially	Employees 40 to 49 yr old	PA chest
Every 3 yr	Employees 39 yr old and under	PA chest
Biennially	Asbestos workers	PA chest
Annually	DOE, U.S. Forest Service, and Wackenhut Services employees	PA chest

1994 to 1998

Frequency	Comment	Projections
Biennially	Employees 50 yr old and older	PA chest
Every 3 yr	Employees 40 to 49 yr old	PA chest
Every 5 yr	Employees 39 yr old and under	PA chest
Biennially	Asbestos workers	PA chest
Annually	DOE, U.S. Forest Service, and Wackenhut Services employees	PA chest

1999 to 2002

Frequency	Comment	Projections
Every 5 yr	Employees in a health surveillance program (including surveillance programs for firefighters, asbestos workers, beryllium workers, etc. and postemployment health surveillance programs)	PA chest
Annually	DOE, U.S. Forest Service, and Wackenhut Services employees	PA chest
Biennially	Asbestos workers	PA chest

2003 to present

Frequency	Comment	Projection
Preemployment	Firefighters, asbestos workers, beryllium workers, nanoparticle workers, workers exposed to respirable crystalline silica (construction workers, maintenance workers, etc.)	PA chest
Every 5 yr	Asbestos workers less than 10 yr from initial exposure, asbestos workers 15–35 yr old and 10 yr or more from initial exposure, firefighters	PA chest
Annually	Asbestos workers greater than 45 yr old and 10 yr or more from initial exposure; beryllium workers; DOE, U.S. Forest Service, and Wackenhut Services employees; nanoparticle workers	PA chest
Biennially	Asbestos workers 35–45 years old and 10 years or more from initial exposure	PA chest
Every 3 yr	Beryllium associated workers (employees with a history of or potential for beryllium exposure), workers exposed to respirable crystalline silica	PA chest
Termination examination	Asbestos workers, beryllium workers, nanoparticle workers, firefighters, workers exposed to respirable crystalline silica	PA chest

a. Sources: Brown [2002, 2022, 2023]; SRNS [2019a,b, 2020a,b, 2021].
b. LAT = lateral; PA = posterior-anterior.

According to the information in Brown [2002], lumbar spine X-rays were not indicated as having been performed for screening, although they appear in some workers' X-ray records, presumably because they were performed for first aid reasons.

3.3 EQUIPMENT AND TECHNIQUES

3.3.1 Photofluorography

Photofluorography (PFG) appears to have been used at SRS from about 1951 to 1960 for mass X-ray screening of groups of people for tuberculosis. In 1953, SRS contracted with Powers X-Ray Service to provide equipment and staff to X-ray 10,000 to 14,000 SRS workers (using PFG), including a subcontract with Dr. Phillip Brown to interpret these PFG views [DuPont 1953].

On July 7, 1953, and February 19, 1954, SRS issued specifications for purchase of a mobile X-ray unit with capability for 70-mm PFG and conventional 14- by 17-in. radiographs [DuPont 1954]. According to the bid specifications, "This mobile x-ray unit shall consist of a complete x-ray unit providing facilities for rapid mass chest x-rays on roll film by using photograph of a fluorescent screen plus facilities for conventional 14" × 17" radiography" [DuPont 1954, p. 7]. Bids were received from Westinghouse, General Electric, and Powers X-Ray Services. Powers X-Ray Services, which specified Picker X-ray equipment, received the contract [DuPont 1954, p. 70]. The Picker X-ray unit was to consist of a blue light-emitting fluorescent screen measuring 16 by 16 in., a 70-mm roll film camera with an f/1.5 lens and 4.375-in. focal length, and phototiming for PFG operation. When operated in the conventional radiography mode, either photo- or manual timing could be selected. The unit could be operated with a range of 0 to 200 mA with a maximum applied kilovoltage of 140 kVp [DuPont 1954].

Measured exposures on the Picker machine in the PFG mode have not been found. However, information submitted to SRS in the Westinghouse bid (which was not accepted but did meet the

specifications for the PFG unit SRS eventually purchased) shows that a satisfactory PFG image of the chest of an average male worker should be able to be obtained using 80 kVp, 20 mAs, and a source-to-image distance (SID) of 40 in. [DuPont 1954, p. 112]. The entrance kerma in air and the resultant organ doses for PFG in this revision are based on the technique factors in the Westinghouse bid. The entrance kerma in air in this TBD (0.5 cGy) compares favorably to that reported in contemporary medical literature (0.5 R) for a PFG unit with an f/1.5 camera lens, 40-in. SID, but slightly higher kVp and half-value layer (HVL) [Laughlin et al. 1957, p. 977].

The Works Technical Department *Monthly Progress Report* for November 1957 makes the following statement about the mobile X-ray unit: “Assistance was given the Project Department and the Medical Department in evaluating several proposed methods for reducing personnel exposures during routine chest x-rays. It was recommended that full size 14" × 17" chest radiographs be used in order to reduce personnel exposure” [DuPont 1957, p. 411].

The statement suggests that by 1957 SRS considered discontinuing use of the PFG mode on the mobile unit. Several references mention use of the mobile unit for X-rays in 1962, 1966, and 1991 [Cooley 1966; Rampey 1966; DuPont 1961; Wiley 1991], but it is assumed these references concern the use of the mobile X-ray machine in the conventional radiographic mode rather than the PFG mode. Given that the mobile Picker machine had both PFG and conventional radiographic (14- by 17-in. film) capability, and that by 1957 SRS was aware of the higher doses from the use of PFG, it is reasonable to assume that references to use of the mobile Picker machine after about 1957 are to its use in the conventional radiographic mode rather than the PFG mode. In the SRS claims received to date that contain X-ray records, the latest documented PFG was in 1960. Approximately 150 SRS cases with X-ray records were reviewed and analyzed. Thirteen of these cases had recorded PFG, all within the period from 1952 to 1960.

Documentation of PFG is not common in the claim files. There could be several reasons for this. It is possible that these old films were kept separately, especially if they remained on the roll rather than cut and filed in individual film jackets, or that they were disposed of or lost, or that errors were made in recording individual workers’ X-rays. In the claims where X-rays were provided, photofluorographs are documented by various methods. The dose reconstructor might see notations such as “roll film,” “70 mm film,” “100 mm film,” “35 mm film,” or “7 × 8 cm film,” all of which should be interpreted as PFG [Birkelo et al. 1947, p. 359; Van Allen 1951, p. 832].

Dose reconstructors should assume that workers had annual PFG examinations through 1960 unless the worker’s X-ray records indicate otherwise.

3.3.2 Radiography

A description of the X-ray equipment at SRS is in Table 3-2. The X-ray equipment descriptions from SRS are Type I equipment (1950 to 1970) [Cooley 1966, 1967], Type II equipment (1971 to July 1985), Type III equipment (August 1985 to May 1999), Type IV equipment (June 1999 to 2004) [Brown 2002; ORAUT 2009], Type V equipment (2005 to September 30, 2014) [Brown 2022, pp. 8–10], and Type VI equipment (October 1, 2014, to present) [Brown 2022, pp. 8–10].

Table 3-2. Description of X-ray and ancillary equipment.

Type	Period	Equipment	Sources
I	1950–1970	Picker mobile X-ray machine (both PFG and conventional radiographic modes), Westinghouse machine (stationary), DuPont 2DC safety screens, DuPont Cronex 7 film, Picker X-ray tube, no grid, manual processing, manual collimator	Cooley 1966, 1967
II	1971–07/1985	Machine not specified,[a] DuPont Daylight Hi-Speed screens, DuPont Cronex 7 film, Picker X-ray tube, stationary 12:1 grid, PAKO 3-minute film processor, manual collimator	Brown 2002; ORAUT 2009
III	08/1985–05/1999	Technomed,[b] DuPont Daylight Cronex 10 TL film, Quanta III screens, TecRad manual collimator, Technomed Recipromatic Upright Bucky 12:1 grid, Kodak M6AW 90-s X-ray film processor, Eureka X-ray tube	Brown 2002; ORAUT 2009
IV	06/1999–2004	Universal machine AGFA Cronex 10TK film, AGFA Curix cassettes with ortho regular screens, AGFA multiloader processor, TecRad manual collimator, Eureka Rad 68 X-ray tube, Technomed Recipromatic upright bucky 12:1 grid	Brown 2002; ORAUT 2009
V	2005–09/2014	Universal Raymaster 625 Model 4604, VIDAR Diagnostic Pro Advantage digitizer, and the Minolta Regius 110 digitizer	Brown 2022, pp. 8–10
VI	10/2014–present	Mobilex USA mobile radiographic unit, Vision X-ray controller, Toshiba X-ray tube, mAs only unit	Brown 2022, pp. 8–10

a. The X-ray machine itself is not specified by SRS. It is assumed for this period that the machine is the same Westinghouse machine in Room 719-A from the earlier period.
b. The X-ray machine itself is not specified by SRS. A Technomed machine is assumed for this period because a Technomed Upright Bucky device is mentioned by SRS.

3.3.3 Technique Factors

An internal document from November 4, 1966, mentions the calibration of medical X-ray units at SRS [Cooley 1966]. The document provides measurements for the stationary Westinghouse unit in Building 719-A only and states that the Picker mobile unit that was not currently in use should be calibrated in January 1967 when it would be used again (presumably in the radiographic mode). A followup memorandum includes not only the technique factors for the mobile Picker machine, but also the results of thermoluminescent dosimeter measurements made on the backs and chests of nine workers during their chest X-rays [Cooley 1967]. The technique factors are in Table 3-3, and the organ doses are discussed in the organ dose section.

Two documents mention total filtration as 2.0-mm Al in the Type I equipment [Cooley 1966; Ericson 2003]. Based on this information and the peak kilovoltage reportedly used during that period, the HVL for Type I equipment (both PFG and radiographic) is assumed to be 2.5-mm Al equivalent. The HVL is assumed as higher (3.5-mm Al equivalent) for the Type II to Type VI equipment due to the higher voltage reportedly used and the added filtration in more modern equipment. The HVLs on which dose conversion factors (DCFs) are chosen for dose reconstruction are in Table 3-4.

Table 3-3. Technique factors for X-ray equipment types.[a]

Machine	Projection[b]	Current (mA)	Voltage (kVp)	Exposure time (s)	Source
Type I (Westinghouse)	PA	200	56	1/10	Cooley 1966
Type I (Picker mobile)	PA	50	75–95	1/10	Cooley 1967
Type I (Westinghouse)	LAT	200	66	1/10	Brown 2002
Type II	PA	300	110–120	1/30	Brown 2002
Type II	LAT	300	120	1/15	Brown 2002
Type III	PA	300	120	1/40	Brown 2002
Type III	LAT	300	120	1/20	Brown 2002
Type IV	PA	300	120	1/40	Brown 2002
Type IV	LAT	300	120	1/20	Brown 2002
Type V	PA	300	120	1/60	Allison 2008
Type V	LAT	300	120	1/30	Allison 2008
Type VI	PA	N/A	70	N/A	Owen 2021
Type VI	LAT	N/A	70	N/A	Owen 2021

a. LAT = lateral; N/A = not applicable; PA = posterior-anterior.
b. The average PA chest measures 24 to 26 cm; the average LAT chest measures 34 cm.

Table 3-4. Entrance air kerma in air for various projections.[a,b]

Machine	Projection	Voltage (kVp)	mAs	HVL	Air kerma rate at 100 cm	SSD (cm)	Entrance kerma in air (cGy)
Type I Picker	PFG	80	20	2.5	0.05 mGy/mAs[c]	73[d]	0.5[e]
Type I	PA	56	20	2.5	0.03 mGy/mAs[c]	154[f]	0.03
Type I	LAT	66	20	2.5	0.04 mGy/mAs[c]	144[g]	0.04
Type II	PA	110–120	10	3.5	1.0 cGy/100 mAs[h]	154[f]	0.044
Type II	LAT	120	20	3.5	1.0 cGy/100 mAs[h]	144[g]	0.1
Type III	PA	120	7.5	3.5	1.0 cGy/100 mAs[h]	154[f]	0.033
Type III	LAT	120	15	3.5	1.0 cGy/100 mAs[h]	144[g]	0.072
Type IV	PA	120	7.5	3.5	1.0 cGy/100 mAs[h]	154[f]	0.033
Type IV	LAT	120	15	3.5	1.0 cGy/100 mAs[h]	144[g]	0.072
Type V	PA	120	5	3.5	1.0 cGy/100 mAs[h]	154[f]	0.021
Type V	LAT	120	10	3.5	1.0 cGy/100 mAs[h]	144[g]	0.048
Type VI	PA	70	5	3.5	0.4 cGy/100 mAs[h]	154[f]	0.008
Type VI	LAT	70	10	3.5	0.4 cGy/100 mAs[h]	144[g]	0.019

a. Source: ORAUT [2024].
b. LAT = lateral; PA = posterior-anterior; SSD = source-to-skin distance.
c. Source: International Commission on Radiological Protection (ICRP) [1982, Figure A-1].
d. 73 cm SSD = 102-cm SID minus 24-cm chest minus 5-cm film-to-chest distance.
e. Rounded up from 0.3 cGy.
f. 154 cm = 183-cm SID minus 24-cm chest minus 5-cm film-to-chest distance.
g. 144 cm = 183-cm SID minus 34-cm chest minus 5-cm film-to-chest distance.
h. Source: National Council on Radiation Protection and Measurements (NCRP) [1989, Table B.3].

A standard SID of 72 in. (183 cm) was used for both posterior-anterior (PA) and lateral (LAT) chest projections, as was standard practice [Cooley 1966; Brown 2002]. Additional information indicated that all the X-ray machines were single phase and that there was no air gap between the worker and the film [Ericson 2003].

3.4 ORGAN DOSES

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

Organ Dose

International Commission on Radiological Protection (ICRP) Publication 34 provides tables of average absorbed dose in milligray (mGy), otherwise known as DCFs, in selected organs for selected X-ray projections at 1-Gy entrance air kerma in air (i.e., without backscatter) and for selected beam qualities (i.e., various HVLs) [ICRP 1982]. Organ doses are found by multiplying the Publication 34 DCFs by the entrance air kerma in air. Entrance air kerma in air can be determined by actual measurement or derived from technique factors. Because few measurements exist for X-ray equipment at SRS, the entrance air kerma in air values used to calculate the X-ray doses in this report were derived using the higher of two average air kerma rate values from Table B.3 of National Council on Radiation Protection and Measurements (NCRP) Report 102 [NCRP 1989] or Figure A-1 from ICRP Publication 34, the technique factors reported by SRS (Table 3-3), and the actual source-to-skin distance (SSD). The data in Figure A-1 were corrected to an SSD of 154 cm. An example calculation of air kerma for a PA examination using the Publication 34 data for a Type 1, Westinghouse machine is:

$$K_{a,i} = K_{a,i\,(\text{ICRP 34})} \times \textit{Current}\ (\text{mA}) \times \textit{ExposureTime}\ (\text{s}) \times \frac{\left(\frac{100}{154}\right)^2}{10K_{a,i\,(1950-1970)}} \qquad (3\text{-}1)$$

$$= 0.030\ (\text{mGy/mAs}) \times 200\ (\text{mA}) \times 0.10\ (\text{s}) \times \frac{\left(\frac{100}{154}\right)^2}{10} = 0.03\ \text{cGy}$$

where

$K_{a,i}$	=	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
$K_{a,i(\text{1950-1970})}$	=	incident air kerma in air from 1950 to 1970 (cGy)

The organ doses in Tables 3-5 through 3-6 were calculated using the SRS parameters.

Skin Dose

Skin doses were determined by the method in ORAUT-OTIB-0006, *Dose Reconstruction from Occupational Medical X-Ray Procedures* [OTIB-0006; ORAUT 2019]. Table 3-6 lists the skin dose guidance for various areas of skin for various projections. Doses were generally determined by analogy with anatomical location for organs not listed in ICRP Publication 34 [ICRP 1982] but specified in the Interactive RadioEpidemiological Program (IREP) following the guidance in OTIB-0006. Table 3-7 lists skin doses from all machines and periods.

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 regarding technique factors for X-ray equipment types, and ICRP Publication 34 DCFs [ICRP 1982]. 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,b]

PA

Organ	PFG 1951–1960[c]	1950–1970	1971–07/1985	08/1985–05/1999	06/1999–2004	2005–09/2014	10/2014–present
Thyroid	8.70E−02	5.22E−03	2.73E−03	2.05E−03	2.05E−03	1.30E−03	4.96E−04
Eye/brain	1.60E−02	9.60E−04	2.73E−03	2.05E−03	2.05E−03	1.30E−03	4.96E−04
Ovaries	5.00E−04	5.04E−03	1.41E−04	1.06E−04	1.06E−04	6.72E−05	2.56E−05
Urinary/bladder	5.00E−04	5.04E−03	1.41E−04	1.06E−04	1.06E−04	6.72E−05	2.56E−05
Colon/rectum	5.00E−04	5.04E−03	1.41E−04	1.06E−04	1.06E−04	6.72E−05	2.56E−05
Testes	5.00E−06	2.73E−04	4.40E−07	3.30E−07	3.30E−07	2.10E−07	8.00E−08
Lung (male)	2.10E−01	1.26E−02	2.49E−02	1.86E−02	1.86E−02	1.19E−02	4.52E−03
Lung (female)	2.26E−01	1.35E−02	2.68E−02	2.01E−02	2.01E−02	1.28E−02	4.88E−03
Thymus	2.26E−01	1.35E−02	2.68E−02	2.01E−02	2.01E−02	1.28E−02	4.88E−03
Esophagus	2.26E−01	1.35E−02	2.68E−02	2.01E−02	2.01E−02	1.28E−02	4.88E−03
Stomach	2.26E−01	1.35E−02	2.68E−02	2.01E−02	2.01E−02	1.28E−02	4.88E−03
Bone surface	2.26E−01	1.35E−02	2.68E−02	2.01E−02	2.01E−02	1.28E−02	4.88E−03
Liver/gall bladder/spleen	2.26E−01	1.35E−02	2.68E−02	2.01E−02	2.01E−02	1.28E−02	4.88E−03
Remainder organs	2.26E−01	1.35E−02	2.68E−02	2.01E−02	2.01E−02	1.28E−02	4.88E−03
Breast	2.45E−02	1.47E−03	4.00E−03	3.00E−03	3.00E−03	1.91E−03	7.28E−04
Uterus	6.50E−04	4.47E−03	1.32E−04	9.90E−05	9.90E−05	6.30E−05	2.40E−05
Bone marrow (male)	4.60E−02	2.76E−03	6.42E−03	4.82E−03	4.82E−03	3.07E−03	1.17E−03
Bone marrow (female)	4.30E−02	2.58E−03	6.20E−03	4.65E−03	4.65E−03	2.96E−03	1.13E−03
ENSD[d]	6.60E−01	4.07E−02	6.18E−02	4.64E−02	4.64E−02	2.95E−02	1.12E−02

LAT

Organ	PFG 1951–1960	1950–1970	1971–07/1985	08/1985–05/1999	06/1999–2004	2005–09/2014	10/2014–present
Thyroid	N/A	5.48E−03	1.51E−02	1.09E−02	1.09E−02	7.25E−03	2.87E−03
Eye/brain	N/A	4.60E−03	1.51E−02	1.09E−02	1.09E−02	7.25E−03	2.87E−03
Ovaries	N/A	2.28E−03	1.60E−04	1.15E−04	1.15E−04	7.68E−05	3.04E−05
Urinary/bladder	N/A	2.28E−03	1.60E−04	1.15E−04	1.15E−04	7.68E−05	3.04E−05
Colon/rectum	N/A	2.28E−03	1.60E−04	1.15E−04	1.15E−04	7.68E−05	3.04E−05
Testes	N/A	1.32E−04	1.00E−05	7.20E−06	7.20E−06	4.80E−06	1.90E−06
Lung (male)	N/A	7.72E−03	2.76E−02	1.99E−02	1.99E−02	1.32E−02	5.24E−03
Lung (female)	N/A	8.80E−03	3.10E−02	2.23E−02	2.23E−02	1.49E−02	5.89E−03
Thymus	N/A	8.80E−03	3.10E−02	2.23E−02	2.23E−02	1.49E−02	5.89E−03
Esophagus	N/A	8.80E−03	3.10E−02	2.23E−02	2.23E−02	1.49E−02	5.89E−03
Stomach	N/A	8.80E−03	3.10E−02	2.23E−02	2.23E−02	1.49E−02	5.89E−03
Bone surface	N/A	8.80E−03	3.10E−02	2.23E−02	2.23E−02	1.49E−02	5.89E−03
Liver/gall bladder/spleen	N/A	8.80E−03	3.10E−02	2.23E−02	2.23E−02	1.49E−02	5.89E−03

Organ	PFG 1951–1960	1950–1970	1971–07/1985	08/1985–05/1999	06/1999–2004	2005–09/2014	10/2014–present
Remainder organs	N/A	8.80E−03	3.10E−02	2.23E−02	2.23E−02	1.49E−02	5.89E−03
Breast	N/A	1.02E−02	3.16E−02	2.28E−02	2.28E−02	1.52E−02	6.00E−03
Uterus	N/A	1.72E−03	1.40E−04	1.01E−04	1.01E−04	6.72E−05	2.66E−05
Bone marrow (male)	N/A	1.48E−03	6.10E−03	4.39E−03	4.39E−03	2.93E−03	1.16E−03
Bone marrow (female)	N/A	1.16E−03	4.80E−03	3.46E−03	3.46E−03	2.30E−03	9.12E−04
ENSD[d]	N/A	5.40E−02	1.41E−01	1.01E−01	1.01E−01	6.74E−02	2.67E−02

a. Source: ORAUT [2024].
b. N/A = not applicable.
c. These organ doses should be doubled if records indicate a stereo PFG.
d. ENSD = entrance skin dose. ENSD is determined by multiplying the entrance air kerma in air by the backscatter factors of 1.355 and 1.405 for HVL of 2.5-mm Al or 3.5-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)
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

Area of skin	PFG	PA through 1970	PA after 1970	LAT after 1970
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. ENSD = entrance skin dose; EXSD = exit skin dose; RSD = remote skin dose.

Table 3-7. Skin dose (rem) from chest projections, all periods.[a,b]

		PA					
Area of skin	PFG 1951–1960[c]	1950–1970	1971–07/1985	08/1985–05/1999	06/1999–2004	2005–09/2014	10/2014–present
Right front shoulder	1.44E−02	8.88E−04	1.80E−03	1.35E−03	1.35E−03	8.60E−04	3.26E−04
Right back shoulder	6.60E−01	4.07E−02	6.18E−02	4.64E−02	4.64E−02	2.95E−02	1.12E−02
Left front shoulder	1.44E−02	8.88E−04	1.80E−03	1.35E−03	1.35E−03	8.60E−04	3.26E−04
Left back shoulder	6.60E−01	4.07E−02	6.18E−02	4.64E−02	4.64E−02	2.95E−02	1.12E−02
Right upper arm to elbow	6.60E−02	4.07E−02	6.18E−03	4.64E−03	4.64E−03	2.95E−03	1.12E−03
Left upper arm to elbow	6.60E−02	4.07E−02	6.18E−03	4.64E−03	4.64E−03	2.95E−03	1.12E−03
Left hand	6.60E−01	4.07E−02	6.18E−03	4.64E−03	4.64E−03	2.95E−03	1.12E−03
Right hand	6.60E−01	4.07E−02	6.18E−03	4.64E−03	4.64E−03	2.95E−03	1.12E−03
Left elbow, forearm, wrist	6.60E−02	4.07E−02	6.18E−03	4.64E−03	4.64E−03	2.95E−03	1.12E−03
Right elbow, forearm, wrist	6.60E−02	4.07E−02	6.18E−03	4.64E−03	4.64E−03	2.95E−03	1.12E−03
Right side of head including ear and temple	6.60E−02	4.07E−03	6.18E−03	4.64E−03	4.64E−03	2.95E−03	1.12E−03
Left side of head including ear and temple	6.60E−02	4.07E−03	6.18E−03	4.64E−03	4.64E−03	2.95E−03	1.12E−03
Front left thigh	1.37E−04	1.17E−05	2.22E−05	1.67E−05	1.67E−05	1.06E−05	4.02E−06
Back left thigh	1.37E−04	1.17E−05	2.22E−05	1.67E−05	1.67E−05	1.06E−05	4.02E−06
Front right thigh	1.37E−04	1.17E−05	2.22E−05	1.67E−05	1.67E−05	1.06E−05	4.02E−06
Back right thigh	1.37E−04	1.17E−05	2.22E−05	1.67E−05	1.67E−05	1.06E−05	4.02E−06

Area of skin	PFG 1951–1960[c]	1950–1970	1971–07/1985	08/1985–05/1999	06/1999–2004	2005–09/2014	10/2014–present
Left knee and below	5.01E−05	4.27E−06	8.11E−06	6.09E−06	6.09E−06	3.87E−06	1.47E−06
Right knee and below	5.01E−05	4.27E−06	8.11E−06	6.09E−06	6.09E−06	3.87E−06	1.47E−06
Left side of face	1.60E−02	9.60E−04	2.73E−03	2.05E−03	2.05E−03	1.30E−03	4.96E−04
Right side of face	1.60E−02	9.60E−04	2.73E−03	2.05E−03	2.05E−03	1.30E−03	4.96E−04
Left side of neck	6.60E−02	4.07E−02	6.18E−03	4.64E−03	4.64E−03	2.95E−03	1.12E−03
Right side of neck	6.60E−02	4.07E−02	6.18E−03	4.64E−03	4.64E−03	2.95E−03	1.12E−03
Back of head	6.60E−02	4.07E−03	6.18E−03	4.64E−03	4.64E−03	2.95E−03	1.12E−03
Front of neck	1.60E−02	9.60E−04	2.73E−03	2.05E−03	2.05E−03	1.30E−03	4.96E−04
Back of neck	6.60E−02	4.07E−02	6.18E−03	4.64E−03	4.64E−03	2.95E−03	1.12E−03
Front torso: base of neck to end of sternum	1.44E−02	8.88E−04	1.80E−03	1.35E−03	1.35E−03	8.60E−04	3.26E−04
Front torso: end of sternum to lowest rib	1.44E−02	8.88E−04	1.80E−03	1.35E−03	1.35E−03	8.60E−04	3.26E−04
Front torso: lowest rib to iliac crest	1.44E−02	8.88E−04	1.80E−04	1.35E−04	1.35E−04	8.60E−05	3.26E−05
Front torso: iliac crest to pubis	1.44E−03	8.88E−05	1.80E−04	1.35E−04	1.35E−04	8.60E−05	3.26E−05
Back torso: base of neck to mid-back	6.60E−01	4.07E−02	6.18E−02	4.64E−02	4.64E−02	2.95E−02	1.12E−02
Back torso: mid-back to lowest rib	6.60E−01	4.07E−02	6.18E−02	4.64E−02	4.64E−02	2.95E−02	1.12E−02
Back torso: lowest rib to iliac crest	6.60E−01	4.07E−02	6.18E−03	4.64E−03	4.64E−03	2.95E−03	1.12E−03
Back torso: buttocks (Iliac crest and below)	6.60E−02	4.07E−03	6.18E−03	4.64E−03	4.64E−03	2.95E−03	1.12E−03
Right torso: base of neck to end of sternum	6.60E−01	4.07E−02	6.18E−02	4.64E−02	4.64E−02	2.95E−02	1.12E−02
Right torso: end of sternum to lowest rib	6.60E−01	4.07E−02	6.18E−02	4.64E−02	4.64E−02	2.95E−02	1.12E−02
Right torso: lowest rib to iliac crest	6.60E−01	4.07E−02	6.18E−03	4.64E−03	4.64E−03	2.95E−03	1.12E−03
Right torso: iliac crest to pubis (right hip)	6.60E−02	4.07E−03	6.18E−03	4.64E−03	4.64E−03	2.95E−03	1.12E−03
Left torso: base of neck to end of sternum	6.60E−01	4.07E−02	6.18E−02	4.64E−02	4.64E−02	2.95E−02	1.12E−02
Left torso: end of sternum to lowest rib	6.60E−01	4.07E−02	6.18E−02	4.64E−02	4.64E−02	2.95E−02	1.12E−02
Left torso: lowest rib to iliac crest	6.60E−01	4.07E−02	6.18E−03	4.64E−03	4.64E−03	2.95E−03	1.12E−03
Left torso: iliac crest to pubis (left hip)	6.60E−02	4.07E−03	6.18E−03	4.64E−03	4.64E−03	2.95E−03	1.12E−03

LAT

Area of skin	PFG 1951–1960	1950–1970	1971–07/1985	08/1985–05/1999	06/1999–2004	2005–09/2014	10/2014–present
Right front shoulder	N/A	5.40E−02	1.41E−01	1.01E−01	1.01E−01	6.74E−02	2.67E−02
Right back shoulder	N/A	5.40E−02	1.41E−01	1.01E−01	1.01E−01	6.74E−02	2.67E−02
Left front shoulder	N/A	2.37E−04	8.62E−04	6.21E−04	6.21E−04	4.14E−04	1.64E−04
Left back shoulder	N/A	2.37E−04	8.62E−04	6.21E−04	6.21E−04	4.14E−04	1.64E−04
Right upper arm to elbow	N/A	5.40E−02	1.41E−01	1.01E−01	1.01E−01	6.74E−02	2.67E−02
Left upper arm to elbow	N/A	2.37E−04	8.62E−04	6.21E−04	6.21E−04	4.14E−04	1.64E−04
Left hand	N/A	5.40E−03	1.41E−02	1.01E−02	1.01E−02	6.74E−03	2.67E−03
Right hand	N/A	5.40E−03	1.41E−02	1.01E−02	1.01E−02	6.74E−03	2.67E−03
Left elbow, forearm, wrist	N/A	5.40E−03	1.41E−02	1.01E−02	1.01E−02	6.74E−03	2.67E−03
Right elbow, forearm, wrist	N/A	5.40E−03	1.41E−02	1.01E−02	1.01E−02	6.74E−03	2.67E−03

Area of skin	PFG 1951–1960	1950–1970	1971–07/1985	08/1985–05/1999	06/1999–2004	2005–09/2014	10/2014–present
Right side of head including ear and temple	N/A	4.60E−03	1.41E−02	1.01E−02	1.01E−02	6.74E−03	2.67E−03
Left side of head including ear and temple	N/A	4.60E−03	1.41E−02	1.01E−02	1.01E−02	6.74E−03	2.67E−03
Front left thigh	N/A	7.26E−06	2.40E−05	1.73E−05	1.73E−05	1.15E−05	4.57E−06
Back left thigh	N/A	7.26E−06	2.40E−05	1.73E−05	1.73E−05	1.15E−05	4.57E−06
Front right thigh	N/A	7.26E−06	2.40E−05	1.73E−05	1.73E−05	1.15E−05	4.57E−06
Back right thigh	N/A	7.26E−06	2.40E−05	1.73E−05	1.73E−05	1.15E−05	4.57E−06
Left knee and below	N/A	2.66E−06	8.79E−06	6.33E−06	6.33E−06	4.22E−06	1.67E−06
Right knee and below	N/A	2.66E−06	8.79E−06	6.33E−06	6.33E−06	4.22E−06	1.67E−06
Left side of face	N/A	4.60E−03	1.41E−02	1.01E−02	1.01E−02	6.74E−03	2.67E−03
Right side of face	N/A	4.60E−03	1.41E−02	1.01E−02	1.01E−02	6.74E−03	2.67E−03
Left side of neck	N/A	4.60E−03	1.41E−02	1.01E−02	1.01E−02	6.74E−03	2.67E−03
Right side of neck	N/A	4.60E−03	1.41E−02	1.01E−02	1.01E−02	6.74E−03	2.67E−03
Back of head	N/A	4.60E−03	1.41E−02	1.01E−02	1.01E−02	6.74E−03	2.67E−03
Front of neck	N/A	4.60E−03	1.41E−02	1.01E−02	1.01E−02	6.74E−03	2.67E−03
Back of neck	N/A	4.60E−03	1.41E−02	1.01E−02	1.01E−02	6.74E−03	2.67E−03
Front torso: base of neck to end of sternum	N/A	8.80E−03	3.10E−02	2.23E−02	2.23E−02	1.49E−02	5.89E−03
Front torso: end of sternum to lowest rib	N/A	8.80E−03	3.10E−02	2.23E−02	2.23E−02	1.49E−02	5.89E−03
Front torso: lowest rib to iliac crest	N/A	8.80E−03	3.10E−03	2.23E−03	2.23E−03	1.49E−03	5.89E−04
Front torso: iliac crest to pubis	N/A	8.80E−04	3.10E−03	2.23E−03	2.23E−03	1.49E−03	5.89E−04
Back torso: base of neck to mid-back	N/A	8.80E−03	3.10E−02	2.23E−02	2.23E−02	1.49E−02	5.89E−03
Back torso: mid-back to lowest rib	N/A	8.80E−03	3.10E−02	2.23E−02	2.23E−02	1.49E−02	5.89E−03
Back torso: lowest rib to iliac crest	N/A	8.80E−03	3.10E−03	2.23E−03	2.23E−03	1.49E−03	5.89E−04
Back torso: buttocks (Iliac crest and below)	N/A	8.80E−04	3.10E−03	2.23E−03	2.23E−03	1.49E−03	5.89E−04
Right torso: base of neck to end of sternum	N/A	5.40E−02	1.41E−01	1.01E−01	1.01E−01	6.74E−02	2.67E−02
Right torso: end of sternum to lowest rib	N/A	5.40E−02	1.41E−01	1.01E−01	1.01E−01	6.74E−02	2.67E−02
Right torso: lowest rib to iliac crest	N/A	5.40E−02	1.41E−02	1.01E−02	1.01E−02	6.74E−03	2.67E−03
Right torso: iliac crest to pubis (right hip)	N/A	5.40E−03	1.41E−02	1.01E−02	1.01E−02	6.74E−03	2.67E−03
Left torso: base of neck to end of sternum	N/A	2.37E−04	8.62E−04	6.21E−04	6.21E−04	4.14E−04	1.64E−04
Left torso: end of sternum to lowest rib	N/A	2.37E−04	8.62E−04	6.21E−04	6.21E−04	4.14E−04	1.64E−04
Left torso: lowest rib to iliac crest	N/A	2.37E−04	8.62E−05	6.21E−05	6.21E−05	4.14E−05	1.64E−05
Left torso: iliac crest to pubis (left hip)	N/A	2.37E−05	8.62E−05	6.21E−05	6.21E−05	4.14E−05	1.64E−05

a. Source: ORAUT [2024].
b. N/A = not applicable.
c. These organ doses should be doubled if records indicate a stereo PFG.

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 through 1970	Weibull3	2.07081	0.095964	3.02321E−04
PA through 1970	Weibull3	2.895385	0.008308	2.17028E−05
LAT through 1970	Weibull3	2.672861	0.004885	1.45541E−05
PA 01/1971–07/1985	Weibull3	2.080196	0.011521	3.58659E−05
LAT 01/1971–07/1985	Weibull3	2.084044	0.013264	4.20115E−05
PA 08/1985–05/1999	Weibull3	2.080769	0.008643	2.69033E−05
LAT 08/1985–05/1999	Weibull3	2.08384	0.009549	3.01934E−05
PA 06/1999–2004	Weibull3	2.080769	0.008643	2.69033E−05
LAT 06/1999–2004	Weibull3	2.08384	0.009549	3.01934E−05
PA 01/2005–09/2014	Weibull3	2.080322	0.005501	1.70928E−05
LAT 01/2005–09/2014	Weibull3	2.084004	0.006368	2.01279E−05
PA 10/2014–present	Weibull3	2.080624	0.002096	6.49234E−06
LAT 10/2014–present	Weibull3	2.084442	0.002521	7.96812E−06

a. Source: ORAUT [2023].

3.4.1 Dose Reconstruction Guidance

The information given below summarizes instructions given to dose reconstructors in determining organ doses from occupational medical X-ray procedures. For evaluation of probability of causation, X-ray doses are always considered acute and to reflect photons with energies ranging 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 to calculate probability of causation [ORAUT 2017, p. 7].

3.4.1.1 Maximizing Approach

To maximize X-ray dose, assign X-rays based on the frequency in Table 3-1. If there is evidence of more frequent X-rays in the worker's medical record, those X-rays should be assigned. Refer to Tables 3-5 and 3-7 for such doses.

3.4.1.2 Best-Estimate Approach

Because SRS does not provide X-ray records as part of the normal DOE response for records, the medical records must be specifically requested from the site. Assign X-rays based on the actual X-ray records.

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 X-ray source (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 [ORAUT 2019].

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.

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.

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.

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

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

shallow dose equivalent [*Hp(0.07)*]
Dose equivalent in units of rem or sieverts at a depth of 0.07 millimeters (7 milligrams per square centimeter) in tissue equal to the sum of the penetrating and nonpenetrating doses.

skin dose
See *shallow dose equivalent*.

X-ray
See *radiograph*.