DOE Review Release 12/14/2009

Document Title: **Savannah River Site – Occupational Medical Dose**	Document Number: ORAUT-TKBS-0003-3 Revision: 04 Effective Date: 11/30/2009 Type of Document: TBD Supersedes: Revision 03 Occupational Medical Dose Section

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☐ New ☒ Total Rewrite ☐ Revision ☐ Page Change

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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 (2005). 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.

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ACRONYMS AND ABBREVIATIONS

AP	anterior-posterior
C.F.R.	Code of Federal Regulations
cGy	centigray
cm	centimeter
DCF	dose conversion factor
DOE	U.S. Department of Energy
DOL	U.S. Department of Labor
EEOICPA	Energy Employees Occupational Illness Compensation Program Act of 2000
Gy	gray
HVL	half-value layer
ICRP	International Commission on Radiological Protection
in.	inch
IREP	Interactive RadioEpidemiological Program
kVp	kilovolts-peak, applied kilovoltage
LAT	lateral
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
PA	posterior-anterior
PFG	photofluorography
POC	probability of causation
R	roentgen
s	second
SID	source-to-image distance
SRDB Ref ID	Site Research Database Reference Identification (number)
SRP	Savannah River Plant
SRS	Savannah River Site
SSD	source-to-skin distance
TBD	technical basis document
U.S.C.	United States Code
USFS	U.S. Forest Service

WSI	Wackenhut Services, Inc.
§	section or sections

3.1 INTRODUCTION

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

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

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

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

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

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

3.1.1 Purpose

The purpose of this technical basis document (TBD) is to describe the occupational medical dose workers might have received at the Savannah River Site (SRS; formerly the Savannah River Plant (SRP)). Occupational medical dose results from X-ray procedures that were performed for health screening of energy employees during preemployment and annual physical examinations. X-rays that were 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 will be used by the Oak Ridge Associated Universities (ORAU) Team to evaluate the dose workers might have received as a result of these X-ray examinations.

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 with which the examinations or procedures were performed. The X-ray techniques and equipment changed over the years and are presented and discussed in this section as they pertain to dose reconstruction. This TBD presents organ dose tables and supporting documentation to assist dose reconstructors in evaluating occupational doses as a result of these X-ray examinations.

Attributions and annotations, indicated by bracketed callouts and used to identify the source, justification, or clarification of the associated information, are presented in Section 3.6.

3.2 EXAMINATION FREQUENCIES

SRS provided the information on the frequency of the X-ray screening examinations indicated in Table 3-1 (Brown 2002). X-ray frequency was determined by the age of the employee and the type of work the employee performed. NIOSH informed DOE-HQ that it was not necessary to search for occupational X-rays that were performed as a condition of employment. Therefore, not all of the claimant records from the SRS contain all X-ray records (Brown 2002). However, the records will be provided by SRS upon special request if they are necessary to determine the POC. Dose reconstructors will assign dose in accordance with the appropriate frequencies in Table 3-1 unless the X-ray records were requested. In that case, all X-rays performed for screening listed in the worker file are to be included in the reconstruction of occupational medical dose.

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 energy employees' 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 the Savannah River Plant (SRP) from about 1951 to 1960 for mass X-ray screening of groups of people for tuberculosis. In 1953, the SRP contracted with Powers X-Ray Service to provide equipment and staff to X-ray 10,000 to 14,000 SRP employees (using PFG), including a subcontract with a Dr. Phillip Brown for the medical interpretation of these PFG views (DuPont, 1953).

Table 3-1. Frequency of chest X-ray screening.

Period	Frequency	Comment	Projections
1950–1988	Annually	All employees	PA chest
	Annually	Construction and asbestos workers	PA and LAT chest
1989–1993	Annually	Employees 50 years old and older	PA chest
	Biennially	Employees 40 to 49 years old	PA chest
	Every 3 years	Employees 39 years old and under	PA chest
	Biennially	Asbestos workers	PA chest
	Annually	DOE, USFS[a], and WSI[a] employees	PA chest
1994–1998	Biennially	Employees 50 years old and older	PA chest
	Every 3rd year	Employees 40 to 49 years old	PA chest
	Every 5th year	Employees 39 years old and under	PA chest
	Biennially	Asbestos workers	PA chest
	Annually	DOE, USFS[a], and WSI[a] employees	PA chest
1999–2002	Every 5th year	Employees in a health surveillance program (this likely means post-employment health surveillance program)	PA chest
	Annually	DOE, USFS[a], and WSI[a] employees	PA chest
	Biennially	Asbestos workers	PA chest

a. USFS = U.S. Forest Service; WSI = Wackenhut Services, Inc.

On July 7, 1953, and February 19, 1954, the SRP issued specifications for purchase of a mobile X-ray unit with capability for 70-mm photofluorography (PFG) and conventional 14- × 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, who specified Picker X-ray equipment, submitted the low bid that was accepted by the SRP (Savannah River Plant, 1954, pg. 70). The Picker X-ray unit was to consist of a blue light-emitting fluorescent screen measuring 16 × 16 inches, a 70-mm roll-film camera with a f 1.5 lens and 4 3/8 inch focal length, and phototiming for PFG operation. When operated in the conventional radiography mode, either phototiming or manual timing could be selected by the operator. 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 the SRP in the Westinghouse bid (which was not accepted) but that met the specifications for the PFG unit that the SRP eventually purchased states 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 given 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 a f 1.5 camera lens, 40 in. SID, but slightly higher kVp and half-value layer (HVL) (Laughlin et al. 1957, p. 977). The organ doses in earlier revisions were based on data in ORAUT-OTIB-0006, *Dose Reconstruction from Occupationally Related Diagnostic X-Ray Procedures* (ORAUT 2005), which was intended to be used when site-specific data was not available.

The Works Technical Department Monthly Progress Report for November 1957 (DuPont 1957, p. 411) makes the following statement, reproduced in its entirety, 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.*

The above statement suggests that by 1957 the SRP was considering discontinuing use of the PFG mode on the mobile unit. Several references mention the use of the mobile unit for X-rays in 1962, 1966, and 1991 (Cooley 1966; Rampey 1966; DuPont, 1961, 1961; and Wiley 1991), but it is assumed that these references pertain to the use of the mobile X-ray machine in the conventional radiographic mode rather than the PFG mode [1]. In the claims received to date from SRS which contain X-ray records, the latest documented PFG was taken in 1960 [2].

The 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 and not cut and filed in individual film jackets, or that they have been disposed of or lost, or errors were made in recording individual employees' X-rays. In the claims where X-rays were provided, PFGs are documented by a variety of methods. The dose reconstructor might see notations such as "roll film,' "70 mm film," "100 mm film," "35 mm film," or "7 x 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 that was used at the SRS is included in Table 3-2. The X-ray equipment descriptions provided by the SRS are Type I equipment (1950 through 1970) (Cooley 1966, 1967), Type II equipment (1971 to July 1985), Type III equipment (August 1985 to May 1999), and Type IV equipment (June 1999 through present 5-15-2009) (Brown 2002, Brown 2009).

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

	Period	Equipment
Type 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.
Type II	1971–7/1985	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.
Type III	8/1985–5/1999	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.
Type IV	6/1999–present	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.

a. The X-ray machine itself is not specified by the 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 the SRS. A Technomed machine is assumed for this period because a Technomed Upright Bucky device is mentioned by the SRS.

3.3.3 Technique Factors

The specific technique factors for these machines as found in SRS records are in Table 3-3.

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

Machine	Projection	Current (mA)	Voltage (kVp)	Exposure time (s)
Type I[a] (Westinghouse)	PA[c]	200	56	1/10
Type I[b] (Picker mobile)	PA[d]	50	75-95	1/10
Type I[a] (Westinghouse)	LAT[e]	200	66	1/10
Type II[c]	PA	300	110–120	1/30
Type II[c]	LAT	300	120	1/15
Type III[c]	PA	300	120	1/40
Type III[c]	LAT	300	120	1/20
Type IV[c]	PA	300	120	1/40
Type IV[c]	LAT	300	120	1/20

a. Cooley (1966).
b. Cooley (1967).
c. Brown (2002).
d. The average PA chest measures 24 to 26 cm.
e. The average LAT chest measures 34 cm.

An internal document from November 4, 1966, mentions the calibration of medical X-ray units at the SRP (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 again be used (presumably in the radiographic mode). A followup memo by Cooley (Cooley 1967) includes not only technique factors used on the mobile Picker machine, but also results of TLD measurements made on the backs and chests of nine workers during their chest X-rays. The technique factors are listed 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 applied kilovoltage that was 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 to be higher (3.5-mm Al equivalent) for the Type II to Type IV equipment because of the higher voltage reportedly used, and more added filtration in more modern equipment. The HVLs on which dose conversion factors (DCFs) are chosen for dose reconstruction are listed in Table 3-4.

Table 3-4. Entrance air kerma in air for various projections used at the SRS.

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	0.6 mGy/mAs[a]	73[b]	0.5[c]
Type I	PA	56	20	2.5	0.03 mGy/mAs[a]	154[d]	0.03
Type I	LAT	66	20	2.5	0.08 mGy/mAs[a]	144[e]	0.04
Type II	PA	110–120	10	3.5	1.0 cGy/100 mAs[f]	154[d]	0.044
Type II	LAT	120	20	3.5	1.0 cGy/100 mAs[f]	144[e]	0.11
Type III	PA	120	7.5	3.5	1.0 cGy/100 mAs[f]	154[d]	0.033
Type III	LAT	120	15	3.5	1.0 cGy/100 mAs[f]	144[e]	0.083
Type IV	PA	120	7.5	3.5	1.0 cGy/100 mAs[f]	154[d]	0.033
Type IV	LAT	120	15	3.5	1.0 cGy/100 mAs[f]	144[e]	0.083

a. ICRP 34 (1982, Figure A-1).
b. 73 cm SSD = 102-cm SID minus 24-cm chest minus 5-cm film-to-chest distance.
c. Rounded up from 0.3 cGy.
d. 154 cm = 183-cm SID minus 24-cm chest minus 5-cm film-to-chest distance.
e. 144 cm = 183-cm SID minus 34-cm chest minus 5-cm film-to-chest distance.
f. NCRP Report 102 (1997, Table B.3).

A standard SID of 72 in. (183 cm) was used for both posterior-anterior and lateral chest projections, as was standard practice (Cooley 1966; and Brown 2002). Additional information indicated that all of 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 DOSE CALCULATIONS

International Commission on Radiological Protection (ICRP) Publication 34 provides tables of average absorbed dose in milligray (mGy) in selected organs for selected X-ray projections at 1-Gy entrance air kerma in air (i.e., without backscatter) otherwise known as dose conversion factors, 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 the SRS, the entrance air kerma in air values 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 1997) or Figure A-1 from ICRP Publication 34, the technique factors reported by SRS and listed in Table 3-3, and the actual source-to-skin distance (SSD).

For organs without unique DCFs in ICRP Publication 34 (ICRP 1982) but specified in the Interactive RadioEpidemiological Program (IREP) code, DCFs for chest X-rays were generally determined by analogy with anatomical location (Table 3-5). Therefore, IREP code organs in the thoracic cavity but not mentioned in Publication 34 were assigned the same dose as the female lung, and the organs in the head and neck were assigned the same dose as the thyroid (with several exceptions in the case of poorly collimated chest radiographs and PFG as described below).

Table 3-5. ICRP Reference organs used for IREP organs without unique ICRP 34 dose conversion factors for properly collimated chest radiography.

ICRP 34 reference organ	IREP organ
Female Lung	Thymus Esophagus Stomach Bone surface Liver, gall bladder, spleen Remainder organs
Ovaries	Urinary/bladder Colon/rectum
Thyroid	Eye/brain

Collimation

Collimation is an important determinant of organ dose. The DCFs in ICRP Publication 34 (ICRP 1982) are assumed to be appropriate to use for properly collimated beams. However, it is assumed for the purpose of dose reconstruction that collimation practices were poor before 1970 (ORAUT 2005). Therefore, organs that are not normally included in the primary beam of a properly collimated beam would have been included in the primary beam for X-ray examinations before 1970, which increased their dose. For example, the ovaries could have been in the primary beam of a poorly collimated chest X-ray beam. To account for the potential increase in dose for this situation, substitute DCFs are used for dose reconstruction of poorly collimated X-rays. For example, DCFs for the abdomen examination (instead of chest) were used to determine the dose to the ovaries, testes, uterus, urinary bladder, colon, and rectum. The DCF for the anterior-posterior (AP) cervical spine (corrected by a depth dose factor of 0.2 because the chest is performed PA) was used to determine the dose to the thyroid and eye/brain. Substitute DCFs used to determine dose to certain organs from poorly collimated beams are listed in Table 3-6.

Table 3-6. Substitute DCFs to determine dose to certain organs from poorly collimated chest X-ray beams before 1970 (ORAUT 2005).

Organ of interest	Substitute DCFs
Thyroid	AP cervical spine corrected for depth by a factor of 0.2 (NCRP 102, Table B-8, p. 103) for PA projections; LAT cervical spine for LAT projections.
Eye/brain	PA and LAT skull, or PA chest, whichever is larger.
Ovaries and analogues, testes, and uterus	PA and LAT abdomen.

The X-ray beam for PFG is smaller than for conventional radiography of the chest because PFG uses a shorter SID of 40 in. rather than 72 in. Therefore, the poorly collimated PFG beam is assumed to include the thyroid, thoracic organs, liver, gall bladder, spleen, but not the eye/brain, gonads, urinary bladder, or the colon/rectum (ORAUT 2005).

The DCFs and organ doses are listed in Tables 3-8 through 3-10. The doses are in units of rem and assume a quality factor of 1 for X-rays. Skin doses were determined in accordance with the method in ORAUT (2005) and are listed in Tables 3-11 and 3-12 for PA and LAT chest X-rays, respectively. 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.

Table 3-7. Comparison of calculated and measured entrance and exit skin doses for Type I X-ray equipment.

Dose parameter	Calculated Value[a]	Measured Value[b]
Entrance Skin Dose, PA Chest	41 mrem	17-36 mrem
Exit Skin Dose	0.9 mrem	0.5-1 mrem

a. Entrance air kerma in air multiplied by the HVL dependent backscatter factor (ORAUT 2005).
b. Cooley (1967).

Table 3-8. Organ doses from PFG[a] at SRS, 1951 to 1960.

Organ	DCF (mGy per Gy air kerma) (beam quality 2.5 mm aluminum HVL)[b]	Organ dose (rem)[c]
Thyroid	174[d]	8.70E-02
Eye/brain	32	1.60E-02
Ovaries	1	5.00E-04
Urinary bladder	1	5.00E-04
Colon/rectum	1	5.00E-04
Testes	0.01	5.00E-06
Lungs (male)	419	2.10E-01
Lungs (female)	451	2.26E-01
Thymus	451	2.26E-01
Esophagus	451	2.26E-01
Stomach	451	2.26E-01
Bone surface	451	2.26E-01
Liver/gall bladder/spleen	451	2.26E-01
Remainder organs	451	2.26E-01
Breast	49	2.45E-02
Uterus (embryo)	1.3	6.50E-04
Bone marrow (male)	92	4.60E-02
Bone marrow (female)	86	4.30E-02

a. All doses based on SID of 102 cm.
b. DCFs from Tables A.2 through A.8, ICRP Publication 34 (1982).
c. These organ doses should be doubled if records indicate a stereo PFG.
d. DCF for AP cervical spine, corrected for depth by 0.2.

Table 3-9. ICRP Publication 34 DCFs for PA and LAT radiographic chest projections for 2.5- and 3.5-mm Al HVL.[a]

Organ	Projection	DCF (mGy per Gy air kerma) 2.5 mm Al HVL Poor collimation	DCF (mGy per Gy air kerma) 3.5 mm Al HVL Proper collimation
Thyroid	PA	174[b]	62
	LAT	137[b]	151
Eye/brain	PA	32[b]	62
	LAT	137[b]	151
Ovaries	PA	168[b]	3.2
	LAT	57[b]	1.6
Testes	PA	9.1[b]	0.01
	LAT	3.3[b]	0.1
Lungs (male)	PA	419	565
	LAT	193	276
Lungs (female)	PA	451	610
	LAT	220	310
Breast	PA	49	91
	LAT	255	316
Uterus/(embryo)	PA	149[b]	3
	LAT	43[b]	1.4
Bone marrow (male)	PA	92	146
	LAT	37	61
Bone marrow (female)	PA	86	141
	LAT	29	48

a. DCFs from Tables A.2 through A.8, ICRP Publication 34 (1982).
b. Substitute DCFs from Table 3-6.

Table 3-10. Organ doses from PA and LAT chest X-rays at SRS.

Organ	Projection	Organ dose (rem) 1950–1970 Type I	Organ dose (rem) 1971–7/1985 Type II	Organ dose (rem) 8/1985–5/1999 Type III	Organ dose (rem) 6/1999-present Type IV
Thyroid	PA	5.22E-03	2.73E-03	2.05E-03	2.05E-03
	LAT	5.48E-03	1.66E-02	1.25E-02	1.25E-02
Eye/brain	PA	9.60E-04	2.73E-03	2.05E-03	2.05E-03
	LAT	5.48E-03	1.66E-02	1.25E-02	1.25E-02
Ovaries	PA	5.04E-03	1.41E-04	1.06E-04	1.06E-04
	LAT	2.28E-03	1.76E-04	1.32E-04	1.32E-04
Urinary/bladder	PA	5.04E-03	1.41E-04	1.06E-04	1.06E-04
	LAT	2.28E-03	1.76E-04	1.32E-04	1.32E-04
Colon/rectum	PA	5.04E-03	1.41E-04	1.06E-04	1.06E-04
	LAT	2.28E-03	1.76E-04	1.32E-04	1.32E-04
Testes	PA	2.73E-04	4.40E-07	3.30E-07	3.30E-07
	LAT	1.32E-04	1.10E-05	8.25E-06	8.25E-06
Lungs (male)	PA	1.26E-02	2.49E-02	1.86E-02	1.86E-02
	LAT	7.72E-03	3.04E-02	2.29E-02	2.29E-02
Lungs (female)	PA	1.35E-02	2.68E-02	2.01E-02	2.01E-02
	LAT	8.80E-03	3.41E-02	2.56E-02	2.56E-02
Thymus	PA	1.35E-02	2.68E-02	2.01E-02	2.01E-02
	LAT	8.80E-03	3.41E-02	2.56E-02	2.56E-02
Esophagus	PA	1.35E-02	2.68E-02	2.01E-02	2.01E-02
	LAT	8.80E-03	3.41E-02	2.56E-02	2.56E-02
Stomach	PA	1.35E-02	2.68E-02	2.01E-02	2.01E-02
	LAT	8.80E-03	3.41E-02	2.56E-02	2.56E-02
Bone surface	PA	1.35E-02	2.68E-02	2.01E-02	2.01E-02
	LAT	8.80E-03	3.41E-02	2.56E-02	2.56E-02
Liver/gall bladder /spleen	PA	1.35E-02	2.68E-02	2.01E-02	2.01E-02
	LAT	8.80E-03	3.41E-02	2.56E-02	2.56E-02
Remainder Organs	PA	1.35E-02	2.68E-02	2.01E-02	2.01E-02
	LAT	8.80E-03	3.41E-02	2.56E-02	2.56E-02
Breast	PA	1.47E-03	4.00E-03	3.00E-03	3.00E-03
	LAT	1.02E-02	3.48E-02	2.61E-02	2.61E-02
Uterus/(embryo)	PA	4.47E-03	1.32E-04	9.90E-05	9.90E-05
	LAT	1.72E-03	1.54E-04	1.16E-04	1.16E-04
Bone marrow (male)	PA	2.76E-03	6.42E-03	4.82E-03	4.82E-03
	LAT	1.48E-03	6.71E-03	5.03E-03	5.03E-03
Bone marrow (female)	PA	2.58E-03	6.20E-03	4.65E-03	4.65E-03
	LAT	1.16E-03	5.28E-03	3.98E-03	3.98E-03

Table 3-11. Skin dose guidance for various chest projections and time periods.

Area of skin	PFG	<1970 PA Chest	<1970 LAT Chest	>1970 PA Chest	>1970 LAT Chest
R Front Shoulder	EXSD[b]	EXSD[b]	ENSD[a]	EXSD[b]	ENSD[a]
R Back Shoulder	ENSD	ENSD	ENSD	ENSD	ENSD
L Front Shoulder	EXSD	EXSD	EXSD	EXSD	EXSD
L Back Shoulder	ENSD	ENSD	EXSD	ENSD	EXSD

R Upper Arm to Elbow	10% ENSD[c]	ENSD	ENSD	10% ENSD	ENSD
L Upper Arm to Elbow	10% ENSD	ENSD	EXSD	10% ENSD	EXSD
L Hand	ENSD	ENSD	10% ENSD	10% ENSD	10% ENSD
R Hand	ENSD	ENSD	10% ENSD	10% ENSD	10% ENSD
L Elbow, Forearm, Wrist R Elbow, Forearm, Wrist	10% ENSD	ENSD	10% ENSD	10% ENSD	10% ENSD
R Elbow, Forearm, Wrist R Elbow, Forearm, Wrist	10% ENSD	ENSD	10% ENSD	10% ENSD	10% ENSD
R Side of Head (including ear)	10% ENSD	10% ENSD	Eye/Brain	10% ENSD	10% ENSD
L Side of Head (including ear)	10% ENSD	10% ENSD	Eye/Brain	10% ENSD	10% ENSD
Front Left Thigh	RSD (0.52m) [e]	RSD (0.52m)	RSD (0.52m)	RSD (0.52m)	RSD (0.52m)
Back Left Thigh	RSD (0.52m)	RSD (0.52m)	RSD (0.52m)	RSD (0.52m)	RSD (0.52m)
Front Right Thigh	RSD (0.52m)	RSD (0.52m)	RSD (0.52m)	RSD (0.52m)	RSD (0.52m)
Back Right Thigh	RSD (0.52m)	RSD (0.52m)	RSD (0.52m)	RSD (0.52m)	RSD (0.52m)
L Knee and below	RSD (0.86m) [f]	RSD (0.86m)	RSD (0.86m)	RSD (0.86m)	RSD (0.86m)
R Knee and below	RSD (0.86m)	RSD (0.86m)	RSD (0.86m)	RSD (0.86m)	RSD (0.86m)
L Side of Face	Eye/Brain	Eye/Brain	Eye/Brain	Eye/Brain	10% ENSD
R Side of Face	Eye/Brain	Eye/Brain	Eye/Brain	Eye/Brain	10% ENSD
L Side of Neck	10% ENSD	ENSD	Eye/Brain	10% ENSD	10% ENSD
R Side of Neck	10% ENSD	ENSD	Eye/Brain	10% ENSD	10% ENSD
Back of Head	10% ENSD	10% ENSD	Eye/Brain	10% ENSD	10% ENSD
Front of Neck	Eye/Brain	Eye/Brain	Eye/Brain	Thyroid	10% ENSD
Back of Neck	10% ENSD	ENSD	Eye/Brain	10% ENSD	10% ENSD
Front Torso: Base of neck	EXSD	EXSD	Lung	EXSD	Lung

to end of sternum					
Front Torso: End of sternum to lowest rib	EXSD	EXSD	Lung	EXSD	Lung
Front Torso: Lowest Rib to iliac crest	EXSD	EXSD	Lung	10% EXSD	10% Lung
Front Torso: Iliac crest to pubis	10% EXSD[d]	10% EXSD	10% Lung	10% EXSD	10% Lung
Back Torso: Base of neck to mid-back	ENSD	ENSD	Lung	ENSD	Lung
Back Torso: Mid-back to lowest rib	ENSD	ENSD	Lung	ENSD	Lung
Back Torso: Lowest rib to iliac crest	ENSD	ENSD	Lung	10% ENSD	10% Lung
Back Torso: buttocks (Iliac crest and below)	10% ENSD	10% ENSD	10% Lung	10% ENSD	10% Lung
Right Torso: Base of neck to end of sternum	ENSD	ENSD	ENSD	ENSD	ENSD
Right Torso: End of sternum to lowest rib	ENSD	ENSD	ENSD	ENSD	ENSD
Right Torso: Lowest Rib to iliac crest	ENSD	ENSD	ENSD	10% ENSD	10% ENSD
Right Torso: Iliac crest to pubis (R hip)	10% ENSD	10% ENSD	10% ENSD	10% ENSD	10% ENSD
Left Torso: Base of neck to end of sternum	ENSD	ENSD	EXSD	ENSD	EXSD
Left Torso: End of sternum to lowest rib	ENSD	ENSD	EXSD	ENSD	EXSD
Left Torso: Lowest Rib to iliac crest	ENSD	ENSD	EXSD	10% ENSD	10% EXSD
Left Torso: Iliac crest to pubis (L hip)	10% ENSD	10% ENSD	10% EXSD	10% ENSD	10% EXSD

a Entrance skin dose (ENSD) is entrance air kerma in air, multiplied by a backscatter factor of 1.35 and 1.4 for 2.5 mm Al HVL and 3.5 mm Al HVL respectively, from NCRP Report No. 102 (1997), Table B-8.
b Exit skin dose (EXSD) is the entrance skin dose divided by the absorption factor for a 24 or 34 cm chest and appropriate HVL, divided by 0.9 to account for uncertainty in tabulated absorption factors in Table B-7 of NCRP Report 102 (NCRP, 1997).
c. 10% ENSD also called the "Outside but near primary beam" dose (ORAUT 2005).
d. 10% EXSD also called the "Outside but near exit beam" dose (ORAUT 2005).
e. Calculated based on 0.52 m from center of chest (ORAUT 2005).
f. Calculated based on 0.86 m from center of chest (ORAUT 2005).

Table 3-12. Dose in rem to various areas of skin from PA and LAT chest X-rays

Area of skin	PFG 1951-1960	PA Chest 1950-1970	LAT Chest Up 1950-1970	PA Chest 1971-1985	LAT Chest 1971-1985	PA Chest 1985-present	LAT Chest 1985-present
R Front Shoulder	1.47E-02	9.E-04	5.40E-02	1.8E-03	1.54E-01	1.4E-03	1.16E-01
R Back Shoulder	6.75E-01	4.05E-02	5.40E-02	6.16E-02	1.54E-01	4.62E-02	1.16E-01
L Front Shoulder	1.47E-02	9.E-04	2.E-04	1.8E-03	9.E-04	1.4E-03	7.E-04
L Back Shoulder	6.75E-01	4.05E-02	2.E-04	6.16E-02	9.E-04	4.62E-02	7.E-04
R Upper Arm to Elbow	6.75E-02	4.05E-02	5.40E-02	6.2E-03	1.54E-01	4.6E-03	1.16E-01
L Upper Arm to Elbow	6.75E-02	4.05E-02	2.E-04	6.2E-03	9.E-04	4.6E-03	7.E-04
L Hand	6.75E-01	4.05E-02	5.4E-03	6.2E-03	1.54E-02	4.6E-03	1.16E-02
R Hand	6.75E-01	4.05E-02	5.4E-03	6.2E-03	1.54E-02	4.6E-03	1.16E-02
L Elbow, Forearm, Wrist R Elbow, Forearm, Wrist	6.75E-02	4.05E-02	5.4E-03	6.2E-03	1.54E-02	4.6E-03	1.16E-02
R Elbow, Forearm, Wrist R Elbow, Forearm, Wrist	6.75E-02	4.05E-02	5.4E-03	6.2E-03	1.54E-02	4.6E-03	1.16E-02
R Side of Head (including ear)	6.75E-02	4.1E-03	5.5E-03	6.2E-03	1.54E-02	4.6E-03	1.16E-02
L Side of Head (including ear)	6.75E-02	4.1E-03	5.5E-03	6.2E-03	1.54E-02	4.6E-03	1.16E-02
Front Left Thigh	2.E-04	1.E-05	8.E-06	2.E-05	3.E-05	2.E-05	2.E-05
Back Left Thigh	2.E-04	1.E-05	8.E-06	2.E-05	3.E-05	2.E-05	2.E-05
Front Right Thigh	2.E-04	1.E-05	8.E-06	2.E-05	3.E-05	2.E-05	2.E-05
Back Right Thigh	2.E-04	1.E-05	8.E-06	2.E-05	3.E-05	2.E-05	2.E-05
L Knee and below	7.E-05	4.E-06	3.E-06	8.E-06	1.E-05	6.E-06	8.E-06
R Knee and below	7.E-05	4.E-06	3.E-06	8.E-06	1.E-05	6.E-06	8.E-06
L Side of Face	1.60E-02	1.E-03	5.5E-03	2.7E-03	1.54E-02	2.0E-03	1.16E-02

R Side of Face	1.60E-02	1.E-03	5.5E-03	2.7E-03	1.54E-02	2.0E-03	1.16E-02
L Side of Neck	6.75E-02	4.05E-02	5.5E-03	6.2E-03	1.54E-02	4.6E-03	1.16E-02
R Side of Neck	6.75E-02	4.05E-02	5.5E-03	6.2E-03	1.54E-02	4.6E-03	1.16E-02
Back of Head	6.75E-02	4.1E-03	5.5E-03	6.2E-03	1.54E-02	4.6E-03	1.16E-02
Front of Neck	1.60E-02	1.E-03	5.5E-03	2.7E-03	1.54E-02	2.0E-03	1.16E-02
Back of Neck	6.75E-02	4.05E-02	5.5E-03	6.2E-03	1.54E-02	4.6E-03	1.16E-02
Front Torso: Base of neck to end of sternum	1.47E-02	9.E-04	8.8E-03	1.8E-03	3.41E-02	1.4E-03	2.57E-02
Front Torso: End of sternum to lowest rib	1.47E-02	9.E-04	8.8E-03	1.8E-03	3.41E-02	1.4E-03	2.57E-02
Front Torso: Lowest Rib to iliac crest	1.47E-02	9.E-04	8.8E-03	2.E-04	3.4E-03	1.E-04	2.6E-03
Front Torso: Iliac crest to pubis	1.5E-03	9.E-05	9.E-04	2.E-04	3.4E-03	1.E-04	2.6E-03
Back Torso: Base of neck to mid-back	6.75E-01	4.05E-02	8.8E-03	6.16E-02	3.41E-02	4.62E-02	2.57E-02
Back Torso: Mid-back to lowest rib	6.75E-01	4.05E-02	8.8E-03	6.16E-02	3.41E-02	4.62E-02	2.57E-02
Back Torso: Lowest rib to iliac crest	6.75E-01	4.05E-02	8.8E-03	6.2E-03	3.4E-03	4.6E-03	2.6E-03
Back Torso: buttocks (Iliac crest and below)	6.75E-02	4.1E-03	9.E-04	6.2E-03	3.4E-03	4.6E-03	2.6E-03
Right Torso: Base of neck to end of sternum	6.75E-01	4.05E-02	5.40E-02	6.16E-02	1.54E-01	4.62E-02	1.16E-01
Right Torso: End of sternum to lowest rib	6.75E-01	4.05E-02	5.40E-02	6.16E-02	1.54E-01	4.62E-02	1.16E-01
Right Torso: Lowest Rib to iliac crest	6.75E-01	4.05E-02	5.40E-02	6.2E-03	1.54E-02	4.6E-03	1.16E-02
Right Torso: Iliac crest to pubis (R hip)	6.75E-02	4.1E-03	5.4E-03	6.2E-03	1.54E-02	4.6E-03	1.16E-02
Left Torso: Base of neck to end of sternum	6.75E-01	4.05E-02	2.E-04	6.16E-02	9.E-04	4.62E-02	7.E-04
Left Torso: End of sternum to lowest rib	6.75E-01	4.05E-02	2.E-04	6.16E-02	9.E-04	4.62E-02	7.E-04
Left Torso: Lowest Rib to iliac crest	6.75E-01	4.05E-02	2.E-04	6.2E-03	9.E-05	4.6E-03	7.E-05
Left Torso: Iliac crest to pubis (L hip)	6.75E-02	4.1E-03	2.E-05	6.2E-03	9.E-05	4.6E-03	7.E-05

3.5 UNCERTAINTY

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

Information on worker thickness is rarely available, even in the medical literature. However, at SRS entrance skin dose measurements were made on nine workers of varying chest thicknesses (builds)

(Cooley, 1967). While Cooley (1967) does not report the measured chest thicknesses for these nine workers, the entrance skin doses are reported and reflect the increases in exposure needed to radiograph thicker body parts, in this case, chests. Cooley (1967) reports the mean of the measured entrance skin doses as 27 mrem. The standard uncertainty of the range of measurements is 5.6, resulting in an uncertainty of 21% from this source.

Substituting this value into the root mean square calculation for combined uncertainty described in OTIB 0006 (ORAUT 2005) instead of the 10% value used in that document, the resultant standard uncertainty is 34% from these five sources. Rounding this up to 35% would seem to provide an adequate and suitably conservative indication of uncertainty. For further conservatism, it may be appropriate to assume that errors are all positive and that only +35% should be used as suggested in ORAUT-OTIB-0006 (ORAUT 2005).

3.6 ATTRIBUTIONS AND ANNOTATIONS

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

[1] Thomas, Elyse M. Oak Ridge Associated Universities. Health Physicist. March 2009. Given that the mobile Picker machine had both PFG and conventional radiographic (14 x 17 film) capability, and that by 1957 SRP was aware of the higher doses delivered with 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, and not the PFG mode.

[2] Thomas, Elyse M. Oak Ridge Associated Universities. Health Physicist. March 2009. Approximately 150 SRS cases with X-ray records were reviewed and analyzed. Thirteen of these cases had recorded PFG, all within the dates of 1952-1960.

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Glossary

air kerma

Air kerma in air is the sum of kinetic energy of all charged particles liberated per unit mass. The unit is the joule per kilogram (J kg^{-1}) and is given the special name gray (Gy).

gray (Gy)

The International System of Units unit of absorbed dose (1 Gy = 1 joule per kilogram).

ionizing radiation

Electromagnetic or particulate radiation capable of producing charged particles through interactions with matter.

rad

The traditional unit of absorbed dose (one rad = 100 ergs per gram of material absorbing the radiation energy).

rem

The rem is the traditional unit of dose equivalent, which is equal to the product of the absorbed dose in rad and the quality factor of the radiation (1 rem = 0.1 Gy).

skin dose

Absorbed dose at a tissue depth of 7 mg/cm^2 ~ 0.07 mm in tissue.

X-ray

(1) Ionizing electromagnetic radiation of external nuclear origin, or (2) a radiograph.