ORAU Team **Dose Reconstruction Project for NIOSH** Technical Basis Document for the Los Alamos National Laboratory – Occupational Medical Dose	Document Number: ORAUT-TKBS-0010-3 Effective Date: 12/29/2004 Revision No.: 00 Controlled Copy No.: _____ Page 1 of 23

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ACRONYMS AND ABBREVIATIONS

AP   anterior-posterior

cm   centimeter

DCF   dose conversion factor
DOE   U.S. Department of Energy

ESE   Entrance Skin Exposure

Gy   Gray

HVL   half value layer

ICRP   International Commission on Radiological Protection
in.   inch
IREP   Interactive RadioEpidemiological Program

kerma   kinetic energy released in matter
keV   kiloelectron-Volt
kVp   kilovolt-peak

LANL   Los Alamos National Laboratory
LASL   Los Alamos Scientific Laboratory
LAT   lateral

mAs   milliampere-second
mGy   milliGray
mm   millimeter
mR   milliroentgen

NCRP   National Council on Radiation Protection and Measurements

PA   posterior-anterior
PFG   photofluorography

R   roentgen
rad   cgs unit for absorbed dose
rem   cgs unit for dose equivalent
RMS   root mean square

SID   Source-to-Image Distance
SSD   Source-to-Skin Distance

TBD   technical basis document

UC   University of California

U.S.C   United States Code

WB   whole body

3.1   INTRODUCTION

Technical Basis Documents (TBDs) and Site Profile Documents are general working documents that provide guidance concerning 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 the National Institute for Occupational Safety and Health 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 facility" as defined in the Energy Employee Occupational Illness Compensation Program Act of 2000 (42 U.S.C. § 7384l (5) and (12)).

Los Alamos National Laboratory (LANL) required pre-employment and annual physical examinations as part of its occupational health and safety program. These medical examinations typically included diagnostic chest X-rays. The doses from these diagnostic procedures depended not only on the characteristics of the X-ray machine and the procedures used, but also on the frequency of the examinations.

3.2   EXAMINATION FREQUENCIES

The frequency of examinations differed significantly over the years. Occupational X-rays might have occurred more frequently than the schedule indicated in Table 3-1. Supplemental claimant-specific frequency data might be recorded in the claimant file provided by the U.S. Department of Energy (DOE).

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

Period	Frequencies	Comment
1943-1963	Semiannual	All UC and Zia Company workers
1964-1984	Annual	Beryllium*, Health Research Laboratory workers
	Annual	All new hire baselines
1985-1990	Annual	All employees
	Annual	All new hire baselines
1991-1992	Annual	All new hire baselines
	Annual	Asbestos-beryllium-silica-cadmium-carcinogens*
1992-1994	Annual	Asbestos-beryllium-silica-cadmium*
1994-2001	Annual	Cadmium*
	Based on age and years of exposure**	Asbestos-beryllium-silica*
2001-present	Every 5 years	Beryllium*
	Based on age and years of exposure**	Asbestos*

*   Specified for workers listed as potentially exposed to particular hazards;
**   Estimated exposure frequencies:

(*) Years of exposure	Age of employee		
	15-35	35-45	45-over
0-10	Every 5 years	Every 5 years	Every 5 years
Over 10	Every 5 years	Every 2 years	Every 1 year

Table 3-1 lists frequencies of chest X-rays for different age groups through the years and identifies specific groups of workers (LASL 1944, LASL 1954). Beginning in the early 1960s, the X-ray units used for screening examinations were in the H-2 Division Occupational Medicine Building (SM-409). According to 1977 and 1978 letter reports, each examination included two chest radiographs

[posterior-anterior (PA) and lateral (LAT)] per patient (Gutierrez and Haynie 1977, 1978). The methods described in 1970s operating procedures are consistent with techniques and methods that were used in the early 1960s and through 1984 (LASL 1972, LASL 1976). The procedures mention that technicians received a copy of the latest revision of National Bureau of Standards Handbook 76 and were expected to be familiar with the pertinent parts of that document. The procedures over the six-year period reflect changes in the methods and techniques used in the 1970s and presumed to continue up through 1984. In 1985, LANL occupational medicine group changed to the Type III equipment.

Laboratory records describe examination techniques used prior to 1957 involved the use of photofluorography (PFG) for the physical screening exams. Two references describe photoroentgen exams as the primary techniques for pre-employment examinations at LASL up until 1957 (Hardy 1950; LASL 1957). Thus, assignment of medical dose for years prior to 1957 must use the use default values presented in Section 3.5.2. If the claim file does not include a specification of the type of examination performed (i.e., chest radiograph or PFG) prior to 1957 then the dose reconstructors should calculate doses using the default PFG parameters in Section 3.5.2, which will produce claimant-favorable dose estimates. Because PFG was discontinued in 1956 (according to LASL 1957), all examinations after that date are assumed to be chest radiographs using DCFs published in International Commission on Radiological Protection (ICRP) Publication 34 (ICRP 1982). For chest examinations between 1957 and 1964, the unavailability of specific information on beam quality has led to the recommendation that the similar default values for dose conversion factors from ICRP 34 (ICRP 1982) should also be used for chest radiographs for that particular period. These dose conversion factors (DCFs) assume minimum collimation for calculating organ doses.

Specific organ doses attributed to PA chest X-rays are calculated on the basis of the DCFs identified in ICRP Publication 34 (ICRP 1982). Organ doses from LAT chest radiography have been estimated by assuming the LAT Entrance Skin Exposure (ESE) is 2.5 times higher than the PA ESE (ORAU 2003a). The organ doses for the LAT views are then calculated by using the DCFs for these LAT views provided in Tables A.2 through A.8 of ICRP (1982). For organs not listed in ICRP Publication 34 but specified in the Interactive RadioEpidemiological Program (IREP) computer code, doses were determined by analogy with anatomical location (see Table 3-5 in Section 3.5). Therefore, IREP code organs not included in ICRP Publication 34 were assigned the following equivalent surrogate doses:

> Thoracic cavity = lungs
> Head and neck organs (including eye, brain) = thyroid

The head and neck organ (i.e., eye/brain) dose estimates are likely to be somewhat greater than doses actually incurred (hence claimant-favorable) due to dose reduction factors experienced in comparison with the surrogate organs. These reductions are due to increased average distance from the X-ray beam or, in the case of the brain, due to attenuation by the bony cranium. In view of the variations in organ dose described in ICRP (1982), the higher of the doses listed for male or female was assumed.

3.3 EQUIPMENT AND TECHNIQUES

This TBD assumes that LANL medical practices followed accepted standards for radiology, including practices used during the 1940s and 1950s to minimize dose to the patient. However, there was the potential for significant dose from occupational medical X-ray examinations depending on the type of equipment, the technique factors, and the number of radiographic and PFG examinations performed through the years (Cardarelli et al. 2002). LANL medical records include notations in individual worker files regarding the date and purpose of X-ray examinations.

X-ray organ dose estimates for occupational radiographic X-rays administered at LANL have been calculated for all the different types of X-ray equipment employed over the operational period. From 1943 through 1956, Type I equipment was utilized as an alternative to PFG for a limited examinations (see Table 3-7 in Section 3.5 and Table 3-8 in Section 3.6 for DCFs). For example, in 1953 LASL performed 1508 "minifilms" (i.e., PFGs) versus 204 14" x 17" standard film X-ray examinations (LASL 1954). The remaining types of X-ray equipment employed are designated Type II (used from 1964 through 1984), Type III (1985 through 1994), Type IV (1995 through 2002), and Type V (2003 to the present). Table 3-2 lists all types of X-ray equipment used at LANL. Tables 3-3 and 3-4 list the specific technique factors and reported or estimated beam quality factors representative of these different machines and their methods of operation.

Table 3-2. X-ray equipment used at LANL.

Technique	Period	Equipment
PFG[a]	1943-1956	Unknown, 70mm fluororoentgenogram
Type I	1943- 1963	Unknown minimal collimation
Type II	1964-1976	General Electric KX810; 6.75-mm Al equivalent total filtration was used (LASL 1978, 1976).
Type II	1977-1984	General Electric KX810; 6.75-mm Al equivalent total filtration was used. This was reduced to 4 mm total filtration sometime in 1977 (LASL 1978, 1976)
Type III	1985-1994	General Electric DXD 350IL Control, Single-Phase Generator, Auto Collimator, 12:1 Grid, 3-mm Al equivalent total filtration. Kodak X-Omatic 90 second cold water processor, 400 speed film-screen system, Kodak Lanex cassettes-rare earth. Fuji Ortho G film
Type IV[b]	1995 – 2002	General Electric DXD 350IL Control, Single-Phase Generator, Auto Collimator, 12:1 Grid, 3-mm Al equivalent total filtration. Kodak X-Omatic 90 second cold water processor, 400 speed film-screen system, Kodak Lanex cassettes-rare earth. Fuji Ortho G film
Type V	2003 – present	Cosmos 22 Control, Three-Phase Generator, Varian X-ray tube, Heustis medical collimator. 2.5-mm Al equivalent total filtration. CXDI22 Canon sensor-digital camera.

a. PFG = Photofluorography
b. Type IV equipment same as Type III, different technique factors used.

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

Machine	View	Current (mA)	Voltage (kVp)	Exposure time (sec.)
Type I 1943-1963	Unknown	Unknown	Unknown	Unknown
Type II 1964-1984	PA	200	96	1/20
Type III – 1985 to 1994	PA	200	94-102[b]	1/30
Type IV – 1995 to 2002	PA	200	110	1/60
Type V – 2003	PA	200	104	1/30

a. PA indicates a posterior/anterior view; the average PA chest measures 24 cm, the average lateral chest measures 36 cm.
b. For conservatism (i.e., higher ESE), all exposures assumed to be obtained at 102 kVp.

The periods, specific technique factors, and equipment descriptions are based on document reviews and interviews with current and previous LANL employees. If additional documentation is identified with more specific information (i.e., periods, technique factors, or equipment descriptions), this TBD will be revised.

Because LANL identified no technique factors for Type I equipment, organ dose estimates for such equipment are determined using Table 3-7 (in Section 3.5.2). For both PA and LAT views, a standard Source-to-Image Distance (SID) of 72 in. (183 cm) was maintained for all types. It is assumed that all

the X-ray machines were single-phase except the three-phase Type V unit and that there was no air gap between the patient and the film. Based on the Al filtration (see Tables 3-2 and 3-4), the estimated half value layers (HVLs) obtained from National Council on Radiation Protection and

Table 3-4. Beam quality and HVL values used to determine DCFs for dose calculations.

Machine type	Dates of Use	Beam quality [filtration, Al-equiv., mm] (reported or estimated*)	HVL, based on filtration (NCRP 1989)	HVL used for DCF selection (ICRP 1982)
PFG	1943-1956	Unknown (2.5 mm*)	2.5 mm*	2.5 mm*
Type I	1943-1963	Unknown (2.5 mm*)	2.5 mm*	2.5 mm*
Type II (a)	1964-1976	6.75 mm	7.2 mm**	7.2 mm**
Type II (b)	1977-1984	4.0 mm	3.3 mm	3.5 mm
Type III	1985-1994	3.0 mm	3.1 mm	3.0 mm
Type IV	1995-2002	3.0 mm	3.4 mm	3.5 mm
Type V	2003-Present	2.5 mm	3.4 mm	3.5 mm

*   Assumed, based upon Table 3-6 default per ICRP 34 (ICRP, 1982)
**   Interpolated HVL = 7.2 for 6.75 mm Al filtration calculated from all available HVL data.

Measurements (NCRP) Report 102 (NCRP 1989, Table B.2) are 3.3 mm Al Type II, 3.1 mm Al Type III, 3.4 mm Al Type IV, and 3.4 mm Al Type V equipment. Because of the excessive total filtration (6.75 mm Al) for 1964 through 1976 and because NCRP (1989, Table B.2) has HVLs only for total filtration of up to 3.5 mm Al, an interpolation using all the listed total filtration values was performed. In addition to maximize the HVL and therefore the dose, an assumed peak tube potential of 120 kVp was assumed. Assuming a total filtration of 6.75 mm Al for 1964 to 1976, the HVL is calculated to be 7.2 mm Al. As stated in an October 4, 1976 LASL memorandum, "the total filtration is unusually high" at 6.75-mm Al equivalent (Gutierrez and Haynie 1976). A recommendation was made to lower the total filtration by 2.5 to approximately 4 mm Al. The total filtration was reduced to 4 mm and it is assumed the beam quality was reduced based on the survey recommendations (Gutierrez 1978; Gutierrez and Haynie 1978). Tables 3-2 and 3-4 indicate that filtration was further reduced in subsequent periods as newer types of machines came into use.

DCFs derived for examinations using PFG and Type I equipment are based on default assumptions listed in Table 3-7 below. For examinations using Type II equipment from 1964 to 1976, the special value of DCF had to be calculated by interpolation of all listed HVLs, to estimate the DCFs for the HVL of 7.2 mm Al that was found, as noted above, to be representative of that particular period, and DCF values in ICRP (1982) are presented only for HVL values up to 4mm Al. DCFs for later use of Type II (1977 to 1984), Type IV, and Type V equipment are based on an HVL of 3.5 in Tables A.2 through A.8 in ICRP (1982). The DCFs for Type III equipment are based on an HVL of 3.0 in Tables A.2 through A.8.

Finally, to determine X-ray organ doses, the air kerma (see Tables 3B-1 through 3B-4 in Attachment 3B) is estimated by using the data in Tables 3-2 and 3-3 and in Figure B.1 from NCRP (1989). Tables 3B-1 through 3B-4 list organ doses for PA and LAT 14- x 17–in. chest films.

To determine PFG doses, additional LANL examination program records were reviewed. As part of the LANL physical program instituted in 1954 (Shipman 1955), a 70-mm fluororoentgenogram (photofluorographic chest X-ray) was routinely obtained unless history or physical examination indicated the desirability of a standard 14- x 17-in. radiographic chest film. Because no additional information was identified for LANL PFG chest X-rays, dose estimates were determined using methodology from ORAU (2003b). Table 3-6 (in Section 3.5.2) lists estimated organ doses for PFG examinations.

3.4   ORGAN DOSE CALCULATIONS (TYPES II THROUGH V, 1964 - PRESENT)

This section presents X-ray organ dose estimation methods for occupational X-rays administered at LANL for Type II equipment (used from 1964 through 1984), Type III equipment (1985 through 1994),

Type IV equipment (1995 through 2002), and Type V equipment 2003 to the present). For examinations conducted between 1943 and 1963, the following calculation methods do not apply because no technical factors were available for the Type I radiographic or PFG equipment used. For that period the dose reconstructor must use the default values presented in Section 3.6. If the claim file does not indicate the type of exam performed (i.e., chest radiograph or PFG) prior to 1964, base the dose estimates on PFG to be claimant-favorable.

ICRP Publication 34 (ICRP 1982) contains tables of average absorbed dose (mGy) in selected organs for selected X-ray projections at 1-Gy entrance kerma (i.e., air kerma without backscatter), for selected views (including PA and LAT), and for selected beam qualities (i.e., various HVLs). These tables list basic dose conversion factors for converting air kerma to organ dose. Air kerma was obtained from Figure B.1 of NCRP Report 102 (NCRP 1989). The data in Figure B.1 were corrected for a distance of 183 cm. The average air kerma rates for the different machines are calculated using the cGy per mAs provided in NCRP Report 102 for specific voltage, current, phase of the machine, and distance to the film.

Finally, the LANL organ doses are found by multiplying the ICRP (1982) organ dose conversion factors by the modified air kerma factors (ESE). The resulting LANL X-ray organ doses for all machines are listed in Attachment 3B, Tables 3B-1 through 3B-4. Table 3-6 (in Section 3.5.2) lists organ doses from photofluorographic chest X-rays in units of rem. LANL records should indicate the views obtained.

The following formulas were used to calculate the doses in Tables 3B-1 and 3B-3.

Based on the techniques in Table 3-3, the mAs for the types of equipment were calculated for each view:

$$\text{Current (mA)} \times \text{exposure time (sec)} = \text{Current for view (mAs)} \qquad (3\text{-}1)$$

Example for PA view:

        Type II   200 mA × 1/20s = 10 mAs
        Type III 200 mA × 1/30s = 6.67 mAs
        Type IV 200 mA × 1/60s = 3.33 mAs
        Type V   200 mA × 1/30s = 6.67 mAs

The air kerma rate for Type II (1964-1976, 120 kVp) was determined to be 0.16 cGy/100 mAs, Type II (1977-1984, 96 kVp) was 0.14 cGy/100 mAs, Type III (102 kVp), 0.23 cGy/100 mAs, Type IV (110 kVp) 0.28 cGy/100 mAs, and Type V (104 kVp) 0.48 cGy/100 mAs [see Figure B.1 of NCRP (1989)] after applying an inverse square correction factor of 0.3 for a distance of 183 cm. The air kerma was calculated after conversion of the rate to air kerma per mAs.

$$\text{Current for view (mAs)} \times \text{Corrected air kerma rate (cGy/mAs)} = \text{Air kerma (cGy)} \quad (3\text{-}2)$$

Example for PA view:

        Type II   10 mAs × 0.0016 cGy/mAs = 0.016 cGy
        Type II   10 mAs × 0.0014 cGy/mAs = 0.014 cGy
        Type III   6.67 mAs × 0.0023 cGy/mAs = 0.015 cGy
        Type IV   3.33 mAs × 0.0028 cGy/mAs = 0.009 cGy
        Type V   6.67 mAs × 0.0048 cGy/mAs = 0.032 cGy

The air kerma was corrected for the thickness of the chest (24 cm) and for distance between the chest and the plane of the film (5 cm) to obtain the air kerma at skin entrance.

$$\text{Air kerma at 183 cm} \times \text{SID squared} \div \text{SSD squared} = \text{air kerma at skin entrance} \qquad (3\text{-}3)$$

Example for Type IV PA view:

$$0.009 \text{ cGy} \times (183 \text{ cm})^2 \div (154 \text{ cm})^2 = 0.013 \text{ cGy}$$

Air kerma at skin entrance was multiplied by the dose conversion factors in Tables A.2 through A.8 of ICRP (1982) for PA chest and HVL of 3.5 mm-Al equivalent.

$$\text{Air kerma (cGy)} \times \text{Dose conversion factor} = \text{Dose for view (cGy)} \qquad (3\text{-}4)$$

Example for Type IV PA view, dose to thyroid:

$$0.013 \text{ cGy} \times 62 \text{ mGy/Gy} \times 1 \text{ Gy/100 cGy} \times 1 \text{ rad/10 mGy} = 8.06 \times 10^{-4} \text{ rad}$$

Example for Type IV LAT view, dose to thyroid:

The air kerma at the skin entrance for the PA view was multiplied by 2.5 (ORAU 2003a).

Example for Type IV LAT view:

$$0.013 \text{ cGy} \times 2.5 = 0.0325 \text{ cGy} \qquad (3\text{-}5)$$

Air kerma at skin entrance was multiplied by the dose conversion factors in Tables A.2 through A.8 of ICRP (1982) for LAT chest and HVL of 3.5 mm Al.

$$\text{Air kerma (cGy)} \times \text{Dose conversion factor} = \text{Dose for view (cGy)}$$

Example for Type IV LAT view, dose to thyroid:

$$0.0325 \text{ cGy} \times 151 \text{ mGy/Gy} \times 1 \text{ Gy/100cGy} \times 1 \text{ rad/10 mGy} = 4.91 \times 10\text{-}3 \text{ rad} \qquad (3\text{-}6)$$

For Type I equipment used prior to 1964, the tube was equipped with a diagnostic type housing with a beam port that provided minimal collimation. Therefore, organs not normally in the primary beam for PA chest X-rays were included in the primary beam by using ICRP (1982) organ dose conversion factors for procedures in which those organs would normally be included in the primary beam. For example, assuming minimal collimation, the ovaries would be in the primary beam, and dose conversion factors for the abdomen were used. Abdomen dose conversion factors were used for ovaries, embryo, and their analogues; the cervical spine dose conversion factor was used for the thyroid and its analogues; and the PA skull dose conversion factor was used for the eye/brain (see Table 3-5).

3.5   RECONSTRUCTION USING DEFAULT VALUES

Use of default values presented in the following sections is recommended for claims that have incomplete records or documentation of specific technique factors or output measurements. Default values of entrance kerma have been developed for the three most commonly used occupational medical diagnostic X-ray procedures: (1) PA chest radiography; (2) LAT chest radiography; (3) PFG chest films when actual measurement data or knowledge of technique factors were absent. The

Table 3-5. Analogues for IREP organs not included in ICRP 34.

Anatomical location	ICRP 34 reference organ	IREP organ analogues
Thorax	Lung	Thymus Esophagus Stomach Bone surface Liver/gall bladder, spleen Remainder organs
Abdomen	Ovaries	Urinary/bladder Colon/rectum
Head and neck	Thyroid	Eye/brain

default values are maxima or upper-limit values developed from review of patient doses as reported in the literature, machine characteristics, and knowledge of X-ray procedures used during the periods indicated. Thus, it may be assumed that use of default values, when necessary and appropriate, will result in a claimant-favorable results.

Sufficient conservatism was included in the determination of the default values to ensure with near certainty (99+% confidence) that actual exposures from the specified procedures would not exceed the default values. In determining these factors, it was assumed that a minimum filtration was used along with low kilovoltage techniques, slow film speeds with standard development, and no additional collimation or use of cones. Table 3-6 lists default entrance kerma values for the three procedures.

Table 3-6. Default dose values by procedure.

Period	Entrance kerma (cGy)		
	PA chest	LAT chest	PFG chest
Pre-1970	0.20	0.50	3.0
1970-1985	0.10	0.25	NA
Post 1985	0.05	0.13	NA

These default values can be used as described above in lieu of actual measurement data or entrance kerma derived from technique factors.

3.5.1 Application and Reporting of Occupational Medical X-Ray Dose Reconstruction

Table 3-7 lists organ dose conversion factors and organ dose calculations for dose reconstruction for the default case.

3.5.2 Photofluorography

Photofluorography, also known as photoroentgenography, was utilized for routine chest radiography and, as well documented in the literature, typically produces higher patient doses than conventional radiography (Braestrup 1958, p. 140; Laughlin et al. 1957; Moeller, Terrill, and Ingraham 1953). Occupational, diagnostic chest X-rays at the DOE facilities and its predecessor agencies were commonly performed through the use PFGs. Los Alamos also made the use of PFGs for it's pre-employment and routine physical examinations up until 1957 when they stop using this method due to the higher radiation doses to the individuals. LASL reported doses as high as 30 mR per chest exposure (LASL 1958). PFG differed from conventional film radiography due to the facts that the kVp and mAmp settings could be manipulated by the technician and the exposure time was regulated by

the amount of light generated in the unit with a cutoff or maximum exposure time. An exposure of 15 mAs (150 mA for 0.1 second) was sufficient to produce a satisfactory image on 35mm film; larger film required greater exposures (Sante 1954, p. 129).

Typical operating parameters reported for 1950s PFG were 24 mAs at 83 kVp at a target-to-film distance of 36 in. (Braestrup 1958, p. 143), and 30 mAs at 90 kVp with a target-to-film distance of 40 in. and 2.4-mm added filtration. In the absence of data that describe LASL's PFGs, dose reconstructors should assume added filtration of 2.5 mm for dose determinations, which is claimant-favorable (Feldman et al. 1958). The reported gonadal doses were 0.15 mrad and 0.36 mrad for females and males, respectively, in the United Kingdom (Stanford and Vance 1957), and 1 and 2 mrad for females and males, respectively, in an American study (Laughlin et al. 1957). In another study in the United States, Feldman et al. (1958) reported gonadal exposures equivalent to doses of 0.73 mrad for males and 15 mrad for females, the large difference attributable to assumed collimation. Data in the literature indicate an ESE of about 0.5 to 1 R (Laughlin et al. 1957; Feldman et al. 1958; Moeller, Terrill, and Ingraham 1953).

Measurements at the Hanford Site indicated an ESE of 1.53 R for a 60-mAs PFG exposure at 100 kVp (Rising and Soldat 1959). This is probably an upper limit value based on a large patient and is consistent with an ESE of about 600-700 mR for a 24-30 mAs exposure at somewhat lower kVp. Although the Hanford measured value is probably an upper limit and therefore an overstatement of the actual exposure from PFG to the average patient, dose reconstructors should use the 1.53 R ESE value in the absence of LASL-specific data for PFG.

Organ doses for chest PFG are calculated in an analogous manner to organ doses for conventional radiography using the entrance kerma values. Table 3-7 lists dose conversion factors for the ICRP organs based on a distance of 102 cm and beam quality of 2.5 mm Al HVL. If entrance kerma values are unavailable, dose reconstructors should use default values for organ doses; Table 3-7 lists these default organ doses.

3.6 RECONSTRUCTION OF ORGAN DOSE FROM RADIOGRAPHY EQUIPMENT USING MINIMAL COLLIMATION

Prior to about 1970, X-ray measurement data, techniques, or beam port information might not be available to estimate the collimation of the X-ray beam. Several papers in the literature have considered the effects of cone size and centering on organ doses, and concluded that filtration, kVp, and the smallest possible cone size were most important to reduce these doses. Due to the reported variation in the literature and measurement data on the effects of collimation, it is claimant-favorable to assume the use of minimal or no additional external collimation when measurement data, technique, or other information to describe the collimation are not available for X-ray procedures performed prior to 1970.

Without collimation, organs normally outside the primary beam are exposed to the primary beam. This necessitates the use of dose conversion factors from ICRP (1982) other than those for a PA or LAT chest X-ray, because the ICRP dose conversion factors are based on properly collimated beams. For minimally collimated beams used prior to 1964, the substitute dose conversion factors listed in Table 3-8 were used.

Dose estimates for PFG represent absolute upper limits, and dose reconstructors must use them in the absence of more specific information. At sites where measurements or technique factors are available, the organ doses could very possibly be lower.

Error (deviation from the correct, true, or conventionally accepted value of a quantity) and *uncertainty* (defined in terms of the potential range of a stated, measured, assumed, or otherwise determined

Table 3-7. Organ doses for default entrance kerma values.

Organ	View	Dose conversion factor (mGy per Gy air kerma)[a] HVL 2.5 mm Al for PFG — Beam for PFG includes thyroid, and thoracic organs. It does not include gonads, bladder, or colon/rectum.	Organ dose PFG (rem)	Dose conversion factor (mGy per Gy air kerma)[a] HVL 2.5 mm Al	Organ dose pre-1970 (rem),[b,c] Minimal collimation
Thyroid	PA	174(f)	5.2E-1	174 (f)	3.48 E-2
	LAT			137	6.85E-2
Eye/brain	PA	32	9.60E-2	32	6.40E-3
	LAT			137	6.85E-2
Ovaries	PA	N/A	2.5 E-2 (e)	N/A	2.5 E-2 (e)
	LAT			N/A	1.3 E-2 (e)
Liver/gall bladder/spleen	PA	451	1.35E+00	451	9.02E-2
	LAT			220	1.10E-1
Urinary bladder	PA	N/A	2.5 E-2 (e)	N/A	2.5 E-2 (e)
	LAT			N/A	1.3 E-2 (e)
Colon/rectum	PA	N/A	2.5 E-2 (e)	N/A	2.5 E-2 (e)
	LAT			N/A	1.3 E-2 (e)
Testes	PA	N/A	5.0 E-3 (e)	N/A	5.0 E-3 (e)
	LAT			N/A	2.5 E-3 (e)
Lungs (male)	PA	419	1.26E+00	419	8.38E-2
	LAT			193	9.65E-2
Lungs (female)	PA	451	1.35E+00	451	9.02E-2
	LAT			220	1.10E-1
Thymus	PA	451	1.35E+00	451	9.02E-2
	LAT			220	1.10E-1
Esophagus	PA	451	1.35E+00	451	9.02E-2
	LAT			220	1.10E-1
Stomach	PA	451	1.35E+00	451	9.02E-2
	LAT			220	1.10E-1
Bone surfaces	PA	451	1.35E+00	451	9.02E-2
	LAT			220	1.10E-1
Remainder	PA	451	1.35E+00	451	9.02E-2
	LAT			220	1.10E-1
Breast	PA	49	1.47E-1	49	9.80E-3
	LAT			255	1.28E-1
Uterus (embryo)	PA	N/A	2.5 E-2 (e)	N/A	2.5 E-2 (e)
	LAT			N/A	1.3 E-2 (e)
Bone marrow (male)	PA	92	2.76E-1	92	1.84E-2
	LAT			37	1.85E-2
Bone marrow (female)	PA	86	2.58E-1	86	1.72E-2
	LAT			29	1.45E-2
Skin (d)	PA		4.05E+00		2.70E-1
	LAT				6.75E-1

a. Dose conversion Factors from Tables A.2 through A.9, ICRP (1982).
b. Source-to-Image-Distance 183 cm.
c. Image Receptor Size (cm) 35.6 × 43.2.
d. Calculated using backscatter factor of 1.35 for HVL of 2.5 mm Al from NCRP (1989, Table B-3.
e. Modified from Webster.
f. Dose Conversion Factor for AP c-spine, corrected for depth by 0.2.

value of a quantity) provide an indication of the confidence or validity of the dose estimates. *Error* implies knowledge of what the correct or actual value is, which is, of course, not known. Therefore, the more appropriate factor is uncertainty, which is expressed in terms of a confidence level, which in turn is expressed as a percent. Thus, the 99% confidence level indicates that the correct or true value, although not actually known, has a 99% probability of falling within the range cited. The

Table 3-8. Substitute dose conversion factors.

Organ of interest	Substitute view and organ for which dose conversion to use for minimally collimated beams
Thyroid	AP cervical spine corrected for depth by factor of 0.2 (NCRP 1989, Table B-8) LAT cervical spine
Eye/brain	PA and LAT skull, or PA chest, whichever is larger.
Ovaries and analogues, testes, and uterus	PA and LAT abdomen despite what reference shows, it is unlikely that testes were in primary beam

statement of confidence level typically includes all potential sources of error, both random and systematic; the precision or reproducibility of the measurement; and accuracy, or how close the measurement or estimate of dose comes to the actual or correct value.

In theory, a large number of factors can introduce uncertainties or affect the X-ray machine output intensity and dose to the worker. However, in practice only five factors can reasonably have a meaningful or significant impact on dose uncertainty:

1. Measurement error
2. Variation in applied kilovoltage
3. Variation in beam current
4. Variation in exposure time
5. Distance from the worker to the source of the X-rays [Source-to-Skin Distance (SSD)]

The influence of such other factors as use of screens, grids, reciprocity failure, film speed, and development, while potentially variable, do not affect the beam output intensity *per se* except indirectly insofar as these might determine the exposure settings (i.e., kVp, mA, and time) used.

Medical X-ray doses, when measured, were derived largely from actual measurement of X-ray machine output with R-meters or similar ionization chamber devices suitably designed for measurement of photons in the medical X-ray energy range. If properly calibrated and used, R-meters and similar instruments typically and historically have had an uncertainty of $\pm$2% for photon energies below 400 keV (Kathren and Larson 1969). More recent versions of these instruments might provide a somewhat smaller uncertainty on the order of $\pm$1% (NBS 1985; 1988). To be conservative, the uncertainty range of $\pm$2% should be applied to measurements of X-ray intensity.

Theoretically, for a given set of machine settings and parameters, X-ray output should be constant and unvarying. However, this is not true in practice. Output is essentially constant unless focal, spot loading occurs as might be the case when the power rating of the machine is exceeded. It is unlikely that power ratings were ever exceeded because such an event would be difficult to achieve in practice and could result in damage to the X-ray tube. However, even with the use of constant voltage transformers to control line voltages, slight variations could have occurred in line voltage input or other internal voltages, which in turn could alter the kVp of the output beam. In general, for a given kVp setting, variation in kVp falls within $\pm$5% of the machine setting (Seibert, Barnes, and Gould 1991). Because, as noted above, beam intensity is approximately proportional to the 1.7 power of the applied kilovoltage; this translates to an uncertainty of approximately $\pm$8.6% with respect to output beam intensity in the 80 to 100 kVp range used for diagnostic chest radiographs. For conservatism, this is rounded up to $\pm$9%.

Similarly, slight variations in tube current are normal; as a tube ages, or heats up from use, current can change and typically will drop. With all other factors constant, beam intensity will be reduced in direct proportion to the change in tube current. Typically, the reduction in beam output from current variation is not more than a few percent under normal operating conditions. Large decreases are

readily detectable and manifest themselves as underexposed radiographs and result in required maintenance of the machine to restore the output or, as a temporary measure, an increase in the current or kVp to provide the necessary intensity for proper radiography. For a given kVp setting, the output of the beam is a function of the tube current, which in turn is measured by a milliammeter, which measures average tube current. The measurement is subject to uncertainties and there might be minor changes in output as the tube heats from normal use. These variations are typically small, and the estimated uncertainty in beam intensity or output attributable to current variation is $\pm5\%$.

Another parameter that has potential to affect the dose from a diagnostic radiograph, perhaps significantly, is the time of exposure. The potential importance of this parameter is underscored by noting that virtually all medical diagnostic X-ray units used in the DOE complex were of the full wave rectified type. A full wave rectified machine produces 120 pulses of X-rays per second. Thus, in a typical radiographic exposure time of 1/20 of a second, only six pulses would result. A small error in the timer that resulted in a change of only ±1 pulse would correspondingly affect the output by $\pm17\%$; for an exposure time of 1/30 of a second, the change in output corresponding to a deviation of +1 pulse is $\pm25\%$. Early mechanical timers were notoriously inaccurate; accuracy improved significantly with the introduction of electronic timers. Measurements of reproducibility made in the late 1980s and beyond by the State of Washington for the machines at Hanford suggest that the timers, and indeed the entire X-ray output, were fairly constant. However, for conservatism, the assumed uncertainty in beam output attributable to timers has been taken to be $\pm25\%$.

The final factor likely to affect worker dose relates to distance from the source of the X-rays, which is an important determinant of the entrance skin exposure from which organ doses are calculated. For a given individual, the SSD will be determined largely by body thickness and positioning of the body. For a typical worker, the estimated variation in SSD is no more than a few centimeters, with an upper limit of perhaps 7.5 cm. Using the inverse square, this indicates an uncertainty of $\pm10\%$ from this source.

There are two approaches to determine the combined uncertainty from the five potential sources of dose uncertainty listed above. The first, and most conservative in that it gives the greatest range, would be to assume that the uncertainties are additive, which would give an uncertainty range of:

$$2 + 9 + 5 + 25 + 10 = \pm51\%$$

However, a more reasonable approach would be to assume that the uncertainties are in fact random, and to compute the statistical root mean square (RMS) value. The RMS value is simply the square root of the sum of the squares, and computes as $\pm28.9\%$. Rounding this up to $\pm30\%$ would seem to provide an adequate and suitably conservative indication of uncertainty. Thus, for an individual ESE or derived organ dose, an uncertainty of $\pm30\%$ at the one sigma level can be assumed; to be further conservative, it might be appropriate to assume that errors are all positive, and only +30% should be used.

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ATTACHMENT 3B
OCCUPATIONAL MEDICAL DOSE

3B.1   LANL MEDICAL X-RAY

LANL conducted preemployment and annual physical examinations as part of its occupational health program. These examinations typically included a chest X-ray. For some workers and occupations, chest X-rays could be more frequent.

3B.2   ORGAN DOSES FROM MEDICAL X-RAYS

Organ doses from occupational X-rays at LANL are estimated for all years from 1943 to the present. Table 3-1 of this TBD lists the schedule for these exams for all LANL employees over this period. X-ray organ dose estimates were made for Type I equipment (used from 1943 to 1963), Type II (1964 to 1984), Type III (1985 to 1994), Type IV (1995 to 2002), and Type V (2003 to the present). Minimal collimation was assumed for Type I equipment used prior to 1964. For organs outside the chest cavity, ICRP (1982) organ dose conversion factors other than PA chest were used to ensure that the organ doses reflected their presence in the primary beam. For example, the dose to the eye/brain for Type I equipment assumes that the eye/brain were in the primary beam, so the air kerma at the skin was multiplied by the dose conversion factor for LAT skull. .

Tables 3B-1 through 3B- 7 list LANL organ doses.

Table 3B-1. Doses for organs identified in ICRP 34 (1982) PA chest view.

Period	Frequency	LANL employee	Air kerma (cGy) at skin entrance	Organ doses per PA chest (rem)						
				Thyroid	Ovaries	Testes	Lungs	Breast	Uterus/embryo	Bone marrow
1943–1963 (Type I)[a]	See Table 3-1	See Table 3-1	2.00E-01	3.48E-02	2.50E-02	5.00E-03	9.02E-02	9.80E-03	2.50E-02	1.84E-02
1964-1976 (Type II)	See Table 3-1	See Table 3-1	2.26E-02	3.66E-03	2.37E-04	<2.26E-07	2.78E-02	5.36E-03	2.35E-04	7.64E-03
1977–1984 (Type II)	See Table 3-1	See Table 3-1	1.98E-02	1.22E-03	6.34E-05	<1.98E-07	1.21E-02	1.80E-03	5.94E-05	2.89E-03
1985–1994 (Type III)	See Table 3-1	See Table 3-1	2.12E-02	9.75E-04	3.82E-05	<2.12E-07	1.13E-02	1.46E-03	4.88E-05	2.48E-03
1995–2002 (Type IV)	See Table 3-1	See Table 3-1	1.30E-02	8.06E-04	4.16E-05	<1.3E-07	7.93E-03	1.18E-03	3.90E-05	1.90E-03
2003–present (Type V)	See Table 3-1	See Table 3-1	4.52E-02	2.80E-03	1.45E-04	<4.52E-07	2.76E-02	4.11E-03	1.36E-04	6.60E-03

a. All values based on ORAUT-OTIB-006 (2003).

Table 3B-2. Dose for IREP organs not included in ICRP 34 (1982) PA chest view.

Period	Frequency	LANL employee	Air kerma (cGy)	Organ doses per PA chest (rem)									
				Thymus	Liver/gall bladder/ Spleen	Eye/ brain	Esophagus	Stomach	Urinary bladder	Colon rectum	Bone surface	Skin[a]	Remainder
1943–1963 (Type I)[b]	See Table 3-1	See Table 3-1	2.00E-01	9.02E-02	9.02E-02	6.40E-03	9.02E-02	9.02E-02	2.50E-02	2.50E-02	9.02E-02	2.70E-01	9.02E-02
1964-1976 (Type II)	See Table 3-1	See Table 3-1	2.26E-02	2.78E-02	2.78E-02	3.66E-03	2.78E-02	2.78E-02	2.35E-04	2.35E-04	2.78E-04	3.16E-02	2.78E-02
1977–1984 (Type II)	See Table 3-1	See Table 3-1	1.98E-02	1.21E-02	1.21E-02	1.22E-03	1.21E-02	1.21E-02	6.34E-05	6.34E-05	1.21E-02	2.77E-02	1.21E-02
1985–1994 (Type III)	See Table 3-1	See Table 3-1	2.12E-02	1.13E-02	1.13E-02	9.75E-04	1.13E-02	1.13E-02	3.82E-05	3.82E-05	1.13E-02	2.97E-02	1.13E-02
1995–2002 (Type IV)	See Table 3-1	See Table 3-1	1.30E-02	7.93E-03	7.93E-03	8.06E-04	7.93E-03	7.93E-03	4.16E-06	4.16E-06	7.93E-03	1.82E-02	7.93E-03
2003–present (Type V)	See Table 3-1	See Table 3-1	4.52E-02	2.76E-02	2.76E-02	2.80E-03	2.76E-02	2.76E-02	1.45E-04	1.45E-04	2.76E-02	6.33E-02	2.76E-02

a. Skin dose is entrance skin dose calculated from air kerma, multiplied by a backscatter factor of 1.35 or 1.4 from NCRP (1989), Table B-8, depending on HVL.
b. All values based on ORAUT-OTIB-006 (2003).

Table 3B-3. Doses for organs identified in ICRP 34 (1982) LAT chest view.

Period	Frequency	LANL employee	Air kerma (cGy) at skin entrance	Organ doses per LAT chest (rem)						
				Thyroid	Ovaries	Testes	Lungs	Breast	Uterus/Embryo	Bone marrow
1943–1963 (Type I)a	See Table 3-1	See Table 3-1	5.00E-01	6.85E-02	1.30E-02	2.50E-03	1.10E-01	1.28E-01	1.30E-02	1.85E-02
1964-1976 (Type II)	See Table 3-1	See Table 3-1	5.65E-02	1.64E-02	2.94E-04	5.65E-06	3.79E-02	3.07E-02	2.49E-04	8.14E-03
1977–1984 (Type II)	See Table 3-1	See Table 3-1	4.95E-02	7.47E-03	7.92E-05	4.95E-06	1.53E-02	1.56E-02	6.93E-05	3.02E-03
1985–1994 (Type III)	See Table 3-1	See Table 3-1	5.30E-02	7.05E-03	4.77E-05	5.30E-06	1.42E-02	1.52E-02	4.77E-05	2.54E-03
1995–2002 (Type IV)	See Table 3-1	See Table 3-1	3.25E-02	4.91E-03	5.20E-05	3.25E-06	1.01E-02	1.03E-02	4.55E-05	1.98E-03
2003–present (Type V)	See Table 3-1	See Table 3-1	1.13E-01	1.71E-02	1.81E-04	1.13E-05	3.50E-02	3.57E-02	1.58E-04	6.89E-03

a All values based on ORAUT-OTIB-006 (2003).

Table 3B-4. Dose for IREP organs not included in ICRP 34 (1982) LAT chest view

Period	Frequency	LANL employee	Air kerma (cGy)	Organ doses per LAT chest (rem)									
				Thymus	Liver/gall bladder/ Spleen	Eye/ brain	Esophagus	Stomach	Urinary bladder	Colon rectum	Bone surface	Skin[a]	Remainder
1943–1963 (Type I)[b]	See Table 3-1	See Table 3-1	5.00E-01	1.10E-01	1.10E-01	6.85E-02	1.10E-01	1.10E-01	1.30E-02	1.30E-02	1.10E-01	6.75E-01	1.10E-01
1964-1976 (Type II)	See Table 3-1	See Table 3-1	5.65E-02	3.79E-02	3.79E-02	1.64E-02	3.79E-02	3.79E-02	2.94E-04	2.94E-04	3.79E-02	7.91E-02	3.79E-02
1977–1984 (Type II)	See Table 3-1	See Table 3-1	4.95E-02	1.53E-02	1.53E-02	7.47E-03	1.53E-02	1.53E-02	7.92E-05	7.92E-05	1.53E-02	6.93E-02	1.53E-02
1985–1994) (Type III)	See Table 3-1	See Table 3-1	5.30E-02	1.42E-02	1.42E-02	7.05E-03	1.42E-02	1.42E-02	4.77E-06	4.77E-06	1.42E-02	7.42E-02	1.42E-02
1995–2002 (Type IV)	See Table 3-1	See Table 3-1	3.25E-02	1.01E-02	1.01E-02	4.91E-03	1.01E-02	1.01E-02	5.20E-05	5.20E-05	1.01E-02	4.55E-02	1.01E-02
2003–present (Type V)	See Table 3-1	See Table 3-1	1.13E-01	3.50E-02	3.50E-02	1.71E-02	3.50E-02	3.50E-02	1.81E-04	1.81E-04	3.50E-02	1.58E-01	3.50E-02

a. Skin dose is entrance skin dose calculated from air kerma, multiplied by a backscatter factor of 1.35 or 1.4 from NCRP (1989), Table B-8., depending on HVL.
b. All values based on ORAUT-OTIB-006 (2003).

Table 3B-5.   Total dose for organs identified in ICRP 34 (1982) PA and LAT view.

Period	Frequency	LANL employee	Organ doses per PA and LAT chest (rem)						
			Thyroid	Ovaries	Testes	Lungs	Breast	Uterus/embryo	Bone marrow
1943–1963(Type I)	See Table 3-1	See Table 3-1	1.03E-01	3.80E-02	7.50E-03	2.00E-01	1.38E-01	3.80E-02	3.69E-02
1964–1976 (Type II)	See Table 3-1	See Table 3-1	2.00E-02	5.31E-04	5.88E-06	6.37E-02	3.61E-02	4.84E-04	1.58E-02
1977–1984 (Type II)	See Table 3-1	See Table 3-1	8.69E-03	1.43E-04	5.15E-06	2.74E-02	1.74E-02	1.29E-04	5.91E-03
1985–1994 (Type III)	See Table 3-1	See Table 3-1	8.03E-03	8.59E-05	5.51E-06	2.55E-02	1.67E-02	9.65E-05	5.02E-03
1995–2002 (Type IV)	See Table 3-1	See Table 3-1	5.72E-03	9.36E-05	3.38E-06	1.80E-02	1.15E-02	8.45E-05	3.88E-03
2003–present (Type V)	See Table 3-1	See Table 3-1	1.99E-02	3.26E-04	1.18E-05	6.26E-02	3.98E-02	2.94E-04	1.35E-02

Table 3B-6. Total dose for IREP organs not included in ICRP 34 (1982) PA and LAT view

Period	Frequency	LANL employee	Organ doses per PA and LAT chest(rem)									
			Thymus	Liver/gall bladder/ spleen	Eye/ brain	Esophagus	Stomach	Urinary bladder	Colon rectum	Bone surface	Skin	Remainder
1943–1963 (Type I)	See Table 3-1	See Table 3-1	2.00E-01	2.00E-01	7.49E-02	2.00E-01	2.00E-01	3.80E-02	3.80E-02	2.00E-01	9.45E-01	2.00E-01
1964–1976 (Type II)	See Table 3-1	See Table 3-1	6.57E-02	6.57E-02	2.01E-02	6.57E-02	6.57E-02	5.29E-04	5.29E-04	6.57e-02	1.11E-01	6.57E-02
1977–1984 (Type II)	See Table 3-1	See Table 3-1	2.74E-02	2.74E-02	8.69E-03	2.74E-02	2.74E-02	1.43E-04	1.43E-04	2.74E-02	9.70E-02	2.74E-02
1985–1994) (Type III)	See Table 3-1	See Table 3-1	2.55E-02	2.55E-02	8.03E-03	2.55E-02	2.55E-02	4.30E-05	4.30E-05	2.55E-02	1.04E-01	2.55E-02
1995–2002 (Type IV)	See Table 3-1	See Table 3-1	1.80E-02	1.80E-02	5.72E-03	1.80E-02	1.80E-02	5.62E-05	5.62E-05	1.80E-02	6.37E-02	1.80E-02
2003–present (Type V)	See Table 3-1	See Table 3-1	6.26E-02	6.26E-02	1.99E-02	6.26E-02	6.26E-02	3.26E-04	3.26E-04	6.26E-02	9.83E-02	6.26E-02

Table 3B-7. Organ doses for photofluorography examinations.

Organ	View	Dose conversion factor (mGy per Gy air kerma)[a] HVL 2.5 mm Al for PFG Beam for PFG includes thyroid, and thoracic organs. It does not include gonads, bladder, or colon/rectum.	Organ dose PFG (rem)
Thyroid	PA	174(d)	5.2E-1
	LAT		
Eye/brain	PA	32	9.60E-2
	LAT		
Ovaries	PA	N/A	2.5 E-2 (c)
	LAT		
Liver/gallbladder/spleen	PA	451	1.35E+00
	LAT		
Urinary bladder	PA	N/A	2.5 E-2 (c)
	LAT		
Colon/rectum	PA	N/A	2.5 E-2 (c)
	LAT		
Testes	PA	N/A	5.0 E-3 (c)
	LAT		
Lungs (male)	PA	419	1.26E+00
	LAT		
Lungs (female)	PA	451	1.35E+00
	LAT		
Thymus	PA	451	1.35E+00
	LAT		
Esophagus	PA	451	1.35E+00
	LAT		
Stomach	PA	451	1.35E+00
	LAT		
Bone surfaces	PA	451	1.35E+00
	LAT		
Remainder	PA	451	1.35E+00
	LAT		
Breast	PA	49	1.47E-1
	LAT		
Uterus (embryo)	PA	N/A	2.5 E-2 (c)
	LAT		
Bone marrow (male)	PA	92	2.76E-1
	LAT		
Bone marrow (female)	PA	86	2.58E-1
	LAT		
Skin (b)	PA		4.05E+00
	LAT		

a. Dose conversion factors from Tables A.2 through A.9, ICRP Publication 34 (1982).
b. Calculated using backscatter factor of 1.35 for HVL of 2.5 mm Al from NCRP (1989, Table B-3).
c. Modified from Webster.
d. Dose Conversion Factor for AP c-spine, corrected for depth by 0.2.