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Subject Expert(s): Elyse M. Thomas, Fred Duncan, and Edward D. Scalsky

Site Expert(s): Ron Kathren and Vernon Shockley

Approval:	Signature on File Fred Duncan, Document Owner	Approval Date:	01/04/2010
Concurrence:	Signature on File Chris M. Tornes, Objective 1 Representative	Concurrence Date:	01/04/2010
Concurrence:	Signature on File Scott R. Siebert, Objective 3 Representative	Concurrence Date:	01/04/2010
Concurrence:	Signature on File James P. Griffin, Deputy Project Director	Concurrence Date:	01/05/2010
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PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
09/16/2003	00	First approved issue of the technical basis document, Section 3, for the Hanford Site. Initiated by Edward D. Scalsky
04/11/2005	01	Approved issue of Revision 01. Incorporates numerical changes in tables and adds additional tables. Incorporates formal internal and NIOSH review comments. Initiated by Edward D. Scalsky.
01/07/2010	02	Revised to include the Oblique and Lordotic chest views; change in poor collimation assumption for early years x-ray dose data. Includes Attributions and Annotations section. Incorporates formal internal and NIOSH review comments. Changes some dose conversion factors for pre-1970 to conform to the project wide assumption of poor collimation for that time period. Adds organ dose for the Bucky PA chest performed at Hanford in the 1970s and 1980s. Adds skin dose for all projections and time periods. Constitutes a total rewrite of the document. Training required: As determined by the Objective Manager. Initiated by Edward D. Scalsky and Fred Duncan.

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ACRONYMS AND ABBREVIATIONS

AP	anterior-posterior projection
CFR	Code of Federal Regulations
cm	centimeter
DCF	dose conversion factor
DOE	U.S. Department of Energy
DOL	U.S. Department of Labor
EEOICPA	Energy Employees Occupational Illness Compensation Program Act of 2000
EnSD	entrance skin dose
ESE	entrance skin exposure
Gy	gray
HVL	half-value layer
ICRP	International Commission on Radiological Protection
in.	inch
IREP	Interactive RadioEpidemiological Program
keV	kiloelectron-volt
kVp	peak kilovoltage
LAT	lateral projection
LPO	left posterior oblique projection
mA	milliampere
mAs	milliampere-second
mGy	milligray
mm	millimeter
mR	milliroentgen
mrad	millirad
mrem	millirem
NCRP	National Council on Radiation Protection and Measurements
NIOSH	National Institute for Occupational Safety and Health
ORAU	Oak Ridge Associated Universities
PA	posterior-anterior projection
PFG	photofluorography
POC	probably of causation
R	roentgen
RPO	right posterior oblique
RSD	remote skin dose
s	second
SID	source-to-image distance
SRDB Ref ID	Site Research Database Reference Identification (number)

SSD	source-to-skin distance
TBD	technical basis document
U.S.C.	United States Code
§	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 TBD is to describe Hanford occupational medical X-ray procedures and practices. The Oak Ridge Associated Universities (ORAU) Team will use this information to reconstruct dose from occupational medical X-rays for EEOICPA claims for Hanford workers.

3.1.2 Scope

Under EEOICPA, medical X-rays that were administered in conjunction with preemployment, periodic, or termination physical examinations for screening for disease are recognized as a source of occupational exposure and eligible for inclusion in occupational dose reconstruction. Unlike occupational exposures that were incurred during normal work processes, individual medical X-ray exposures were not monitored, which necessitates establishment of a technical basis for these doses. This report describes the technical aspects of dose reconstruction for medical X-rays that were administered at Hanford for occupational health screening.

Attributions and annotations, indicated by bracketed callouts and used to identify the source, justification, or clarification of the associated information, are presented in Section 3.7.

3.2 TECHNICAL FACTORS THAT AFFECT MEDICAL X-RAY DOSE

A number of factors affect the dose to workers from a medical X-ray procedure. However, many of these factors do not need to be known when performing retrospective dose assessments that are based on actual X-ray beam measurements or on knowledge of several key technical factors. In the absence of direct measurements of the beam itself, dose to workers can be estimated with knowledge of basic machine parameters (peak kilovoltage, current, and time) and assumptions about filtration, collimation, and waveform characteristics. The implications of these factors to worker dose are discussed below, and summarized in Table 3-1.

Table 3-1. Relationship of various technical factors to beam intensity.

Factor	Units	Relationship to beam intensity
kilovoltage	kV	Intensity proportional to 1.7 power of the kVp.
Tube current	mA	Linear.
Exposure time	s	Linear.
Filtration	mm Al	Intensity decreases by ~40% for each additional mm Al.
Distance (d)	cm or in.	Approximately inverse square relations ($1/d^2$).

3.2.1 Kilovoltage and Filtration

X-rays from a typical medical X-ray tube are mostly of bremsstrahlung origin, and as such are comprised of a spectrum of photon energies that range from zero to the peak kilovoltage, which refers to the accelerating potential between the anode and cathode of the X-ray tube. For a typical unfiltered, single-phase X-ray spectrum, the average energy is about one-third of the peak energy. Therefore, most of the X-rays that are produced are much lower in energy than those that correspond to the peak kilovoltage of the beam. The peak kilovoltage, however, determines the maximum energy of X-ray photons that are produced at that machine setting.

Filters, which are specific thicknesses of absorbing material (typically aluminum), are added to the beams of medical X-ray machines. The filters absorb the lowest energy X-rays from the spectrum that have too little energy to penetrate the body to the film and that contribute greatly to absorbed dose. A filtered X-ray spectrum therefore has a correspondingly higher average energy than an unfiltered one.

The effective energy of the X-ray beam is determined primarily by the kilovoltage and the filtration, and is indirectly evaluated empirically using a quantity called the beam quality or half-value layer (HVL). Because the X-ray beam energy influences absorbed dose, an estimate of beam energy, inferred from the beam quality or HVL, is needed for dose reconstruction. HVL measurements can be used if they are available; if not, then information about the total filtration in the X-ray tube and kVp is needed.

Because adding filtration to medical X-ray machines has the potential to reduce absorbed dose to exposed individuals, radiation protection groups began making recommendations on added filtration as early as 1937 (ICRU 1937). The recommendations for filter thicknesses have increased over time. Typical added filtration in the 1940s ranged from zero to 1 mm Al. This was in line with the 1936 recommendations of the U.S. Advisory Committee on X-Ray and Radium Protection [later the National Council on Radiation Protection and Measurements (NCRP)], which called for the equivalent of 0.5 mm Al for radiographic installations (NBS 1936). The NCRP recommended 1 mm Al filtration for radiography of thick parts of the body such as the chest in 1949 (NBS 1949), and this thickness was presumably used at Hanford. Recommended thicknesses were later increased. In 1961, the NCRP recommendation for medical X-ray units called for 2.5 mm total Al filtration (NCRP 1961). This was recommended again in 1968 for medical units operating above 70 kVp (NCRP 1968). These recommended filter thicknesses might not have been used widely for some time after the dates of the recommendations.

The relationship of beam intensity to kVp and filtration is complex and to some extent machine-specific. It is therefore best determined empirically. Beam intensity commonly refers to the radiation output of the machine in terms of air kerma in air. In the absence of empirical data for a specific machine, adequate contemporary empirical and theoretical data exist on which to base radiation output of machines with a reasonable degree of uncertainty. Additional filtration reduces the beam intensity in a generally exponential manner. For a typical single-phase, half-wave, full-wave, or self-rectified machine operating in the range of 50 to 130 kVp, each additional millimeter of aluminum filtration will effect a reduction of about 40% in the beam intensity (Trout, Kelley, and Cathey 1952). Therefore, the approximate intensity reduction that is afforded by any thickness of aluminum filtration can be determined by the following exponential equation:

$$I = I_o e^{-0.4t} \qquad (3\text{-}1)$$

or

$$\ln (I/I_o) = -0.4\ t \qquad (3\text{-}2)$$ where

- t = thickness of aluminum in millimeters
- I = beam intensity with the filter
- I_o = beam intensity without the filter

In the absence of specific measurements or empirical data, this correction can be applied to determine the effect of filtration on beam intensity.

Increasing the kVp will increase the beam intensity. Many empirical studies of beam intensity as a function of voltage show that for a given amount of filtration, increasing the voltage increases the beam intensity according to the 1.7 power of the voltage (BRH 1970, p. 159; Newton and Heid 1976). In the absence of specific measurements or empirical data, this function can be applied to determine the effect of kVp on beam intensity.

3.2.2 Current and Exposure Time

Both the tube current in milliamperes and the exposure time in seconds directly affect the number of X-ray photons that are produced from the X-ray tube. The exposure is often described by the milliampere-seconds, which is the product of X-ray tube current and exposure time. All other factors being equal (e.g., kVp, filtration, development, and film/screen combination), and air kerma in air can be assumed to be proportional to the milliampere-seconds.

3.2.3 Distance

X-ray beam intensity (from the X-ray tube) varies inversely with the square of the distance from the X-ray tube target or focal spot (also known as the source) because the target is very small in comparison with the distances of interest from it. This relationship facilitates the conversion of measurement data that are taken at certain distances to the distances necessary for dose reconstruction.

X-ray procedures are performed at standard source-to-image distances (SIDs), which is the distance between the X-ray tube target and the imaging plane or film. Radiographic chest X-rays (on 14- by 17-in. film) have been performed at a standard 72 in. (183 cm) since the earliest days of radiography including at Hanford (Rising and Soldat 1959). Photofluorography (PFG) of the chest and almost all other radiographic procedures are performed at 36 to 40 in. (92 to 102 cm) SID (Rising and Soldat 1959); 40 in. is the most common.

X-ray dosimetry begins with knowledge of the entrance air kerma in air, which is the air kerma in air at the point where the X-ray beam enters the individual's skin or at the source-to-skin distance (SSD) [formerly called the entrance skin exposure]. Body part thickness varies from one individual to another, and can vary over time in the same individual. This type of information has unfortunately not been recorded for workers at DOE facilities. Dose reconstructors should assume standard body part thicknesses identical to those in International Commission on Radiological Protection (ICRP) Publication 34 (ICRP 1982), national X-ray exposure studies (DHHS 1994), and contemporary literature (Cahoon 1961, pp. 106–107) which results in standard SSDs for dose reconstruction. These are listed in Table 3-2.

Table 3-2. Standard body dimensions for dose reconstruction.

Projection	Part thickness (cm)	SID (cm/in.)	SSD (cm)
PA chest	23	183/72	155
LAT chest	34	183/72	144
AP and AP spot lumbar spine	23	102/40	74
LAT and LAT spot lumbar spine	34	102/40	63

3.2.4 Collimation and Waveform Characteristics

Two other factors that affect worker dose are collimation and waveform. The most common X-ray waveforms are from single-phase, three-phase, and high-frequency generators. Three-phase and high-frequency machines did not become commonplace until the 1980s and 1990s; therefore, single-phase machines are assumed to have been used at Hanford in the early years. The waveform is of no significance when actual radiation output data are available as is the case for Hanford.

Collimation refers to the restriction of the X-ray beam. Even though analysis of beam area data from the early X-ray machines at Kadlec Hospital in Richland where all early Hanford workers were X-rayed seems to indicate that beams were restricted to less than the area of the 14- by 17-in. film by the circular cones (Kirklin et al. 1969), poor collimation is assumed before 1970 for dose reconstruction.

3.2.5 Other Factors That Can Affect Worker Dose

A number of other factors affect the X-ray exposure that is required to obtain a usable radiographic image and therefore have the potential to affect the dose to the worker. Knowledge of these factors is unnecessary for dose reconstruction purposes if beam measurements are available or if the primary machine technical factors of kilovoltage, time, and current are known along with the amount of primary beam filtration. These factors are well documented at Hanford (Rising and Soldat 1959; Norwood et al. 1959).

3.3 TYPE AND FREQUENCY OF X-RAY SCREENING AT HANFORD

Review of the available historical documentation at Hanford from 1943 to the present and a sample of claim file records of Hanford workers reveals that chest X-rays were the most commonly used X-ray procedure for occupational health screening. While there are some lumbar spine examinations listed in the claim file records, they appear to have been clearly performed for on-the-job injuries and therefore should not be included in dose reconstruction (42 CFR Part 82). Chest X-rays at Hanford for which organ doses have been developed (Section 3.5) are:

- Photofluorographic (PFG) chest (4- by 5-in. film)
- Posterior-anterior (PA) chest (14- by 17-in. film)
- Lateral (LAT) chest (14- by 17-in. film)
- PA chest with Bucky (14- by 17-in. film)
- Oblique chests (14- by 17-in. film)
- Lordotic chest (14- by 17-in. film)

By far, the most commonly performed of these over all time periods was the PA chest projection on 14- by 17-in. film. PFG was performed in the early years from 1943 to approximately 1962. The LAT chest projections appear to have been performed regularly for screening only after 2000, although there are a few included in the records before that time. A four-projection chest series that consisted of PA Chest, both oblique chests, and PA with Bucky (grid) projections, appears in the records for workers with asbestos exposure or radiographic findings of possible asbestosis during the 1970s and 1980s. There is evidence that oblique projections increase the diagnostic accuracy of asbestosis and therefore could have been included as a standard screening projection for asbestos workers (Baker and Green 1982). Therefore, the dose from all of these projections should be included in dose reconstruction when they appear in the claim file records.

The lordotic chest projection was an additional projection that was requested by a physician, often to better visualize the apices of the lungs, which are a common location for tuberculosis (TB). It would not have been performed on all workers as a standard screening projection. This is evidenced by the fact that at Hanford, the number of lordotic chest projections is only 2% of the number of PA chest projections in the 10-year period from 1946 to 1956 (Kirklin et al. 1969). Because active TB was a cause for not hiring a potential worker (Cantril 1946), and the lordotic projection might have been necessary to diagnose active TB, the dose from lordotic X-rays in the preemployment examination should be included in dose reconstruction. Since it is not known from the historical evidence whether active TB would disqualify workers after hire, dose reconstructors should also include the dose from the lordotic projection in the periodic screening examinations. The lordotic chest projection is not seen in the claim file records after about 1990.

Table 3-3 shows the frequency of various X-ray procedures for the preemployment, periodic, and termination examinations from Hanford documents (Cantril 1946; Fuqua 1981; Kirklin et al. 1969; Vails 1990). In the early years at the site, periodic X-ray examinations were relatively frequent, and the groups of workers that were identified as at risk received medical examinations at more frequent intervals than other workers (Cantril 1946). It is not clear from the historical records whether these

periodic physical examinations included X-ray screening more frequently than annually. In a few claim files, chest X-rays appear to have been taken more frequently than annually, and these should be included in dose reconstruction unless the records indicate a reason to preclude this, such as a notation with the words "first aid" or "dispensary."

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

Period	Frequency	Comment
Up to 1956	Preemployment[a]	All employees
	Termination[a]	All employees
	Annually[a]	All employees
1956–1980 (PFG until 1962)	Preemployment	All employees
	Termination	All employees
	Annually[a]	All employees
1981–1990	Preemployment[c]	All employees
	Biennial[b]	Age 45 and older
	Every 5 years	Age 45 or less
	Termination	All employees
1990 to present	Physician's discretion[c]	All employees

a. Kirklin et al. (1969, p. 150).
b. Beginning January 4, 1981, protocol was biennial after age 45, and every 5 years for all others (Fuqua 1981).
c. Preemployment and termination X-rays were provided from 1941 to the mid-1990s (Vails 1990). These X-rays were not required after 1990 unless personnel were in a job class that required an X-ray or clinical needs were indicated.

3.4 EQUIPMENT AND TECHNIQUES

All of the X-rays on Hanford workers appear to have been taken at the Kadlec Hospital in Richland from the time it opened in 1944 until 1956 (Cantril 1946; Kirklin et al. 1969). This would have included construction workers because Kadlec Hospital was for many years the only place that could perform X-ray examinations (Norwood 1949, p. 18). While the specific equipment model and manufacturer do not appear to have been recorded in historical records, it is clear from the records that the original equipment was available for actual beam measurements as part of the *Feasibility Study of the Correlation of Lifetime Health and Mortality Experience of AEC and AEC Contractor Employees with Occupational Radiation Exposure* (Mancuso, Sanders, and Brodsky 1966). The technique factors, filter information, and actual beam measurements from this equipment are well documented in Rising and Soldat (1959). Table 3-4 summarizes information about the X-ray equipment, including information about equipment in the later years, which comes primarily from State of Washington X-ray machine registration and inspection records (WDOH 1990–1999).

3.5 ORGAN DOSES

Conversion of entrance air kerma in air to organ dose is made in accordance with published dose conversion factors (DCFs) in Tables A2 to A8 of ICRP Publication 34 (ICRP 1982). The tables provide average absorbed organ doses for common radiographic projections relative to an entrance air kerma in air without backscatter of 1 Gy for various beam qualities in terms of HVL of aluminum. However, the tables do not include all organs that are identified in the Interactive RadioEpidemiological Program (IREP) for dose reconstruction. For organs other than the skin in IREP but without individual DCFs in Publication 34, the DCF for the anatomically closest organ is used in most cases. Therefore, the factor for the lung is applied to all other organs within the thoracic cavity (i.e., thymus, esophagus, liver, gall bladder, spleen, and stomach) as shown in Table 3-5.

Table 3-4. Summary of beam parameters for 14- by 17-in. PA chest projections.

Date range	Machine type	Voltage (kVp)	Tube current (mA)	Exposure time (s)	(mAs)	Added filtration (mm Al)	Assumed HVL (mm Al)	SID (in.)	Entrance skin exposure (mR)	mR/mAs	Reference
1943 - 1959	Unknown	80	500	1/20	25	1.5	2.5	72	79	3.2	Kirklin et al. (1969)
1959–1982	Unknown	80	300	1/30	10	1.5	2.5	72	40	4	Rising and Soldat (1959)
1983–1990	General Electric DXR 750	80	200	1/20	10	2.5	2.5	72	35	3.5	Kathren (1982,1983)
1991–1997	Continental 325	110	200	1/30	6.7	2.5	4.0	72 with grid	21 (assumed)	3.3	Measured at 11.7 mR by WDOH (1990–1999, p. 55), but the 1993 value (p. 20) is used because it was higher for the same settings and machine.
1998–1999	Continental 325	110	300	1/30	10	2.5	4.0	72	17	1.7	WDOH (1990–1999, p. 14)
2/1999–present	XMA-360	110	300	1/60	5	2.5	4.0	72	11	2.2	WDOH (1990–1999, p. 4)

Table 3-5. General scheme for DCFs for IREP organs not included in ICRP Publication 34 (ORAUT 2005).

Anatomical location	ICRP Publication 34 DCF (ICRP 1982)	IREP organ without specific DCF
Thorax	Lung	Thymus Esophagus Stomach Bone surface Liver, gall bladder, spleen Remainder organs
Abdomen	Ovaries	Urinary bladder Colon/rectum
Head and neck	Thyroid[a]	Eye/brain[a]

a. For PFG, because of the shorter SID than conventional chest radiography, and as a result of assuming poor collimation in conventional 14- by 17-in. chest radiography before 1970, the thyroid dose is based on the DCF for the cervical spine, and the eye/brain dose is based on the DCF for the chest because it is larger than the DCF for the PA skull (ORAUT 2005).

Because an appreciable fraction of the skeleton, in particular the trabecular bone that has a large surface-to-volume ratio and the sternum that is a primary location of red marrow in the adult, lies within the trunk, the factor for the lung is also applied to the bone surfaces and remainder organs. For organs in the abdomen (i.e., urinary bladder, and colon/rectum) the DCF for the ovary is used. For the eye/brain, the DCF for the thyroid is used. There are a few exceptions to this general scheme in which the edge of the X-ray beam in relation to the organ might require the use of another DCF for the best dose estimate.

As mentioned above, selection of the appropriate DCF also depends on knowledge of the beam quality or HVL. Measured beam quality data for the X-ray machines before about 1990 at Hanford were not found. However, the kVp and filtration were known, and an estimate of beam quality for the X-ray machines at Hanford could be made from these data. Because for a given amount of filtration and exposure, absorbed organ dose increases as a function of HVL and for conservatism the upper limit on the likely beam quality is rounded to match the closest value in the tables in ICRP Publication 34 (ICRP 1982). For the period before 1991, beam quality that was expressed as HVL was conservatively estimated to be 2.5 mm Al; after 1991, the estimate was 4.0 mm Al. These values are greater than the 1.75 and approximately 3.5 mm Al values that would be derived from Table A16 of Publication 34, and therefore are favorable to the claimant.

3.5.1 Chest Photofluorography (PFG)

The organ dose values for PFG at Hanford are based on actual measurements of entrance air kerma in air that were made with a phantom. The potential for high exposure from this procedure was recognized by H. Parker, who cited studies in 1943 and 1945 and noted that the entrance exposure was about 1 R but could be as much as 2.5 R (Parker ca. 1947). The measured value for entrance exposure of 1.51 R for 4- by 5-in. PFG at Hanford (Kirklin et al. 1969) is essentially the same as the value of 1.53 R reported in Rising and Soldat (Rising and Soldat 1959), and is consistent with the range of values Parker (ca. 1947) observed. The higher value of 1.53 R was used for dose calculations. This value is assumed to be for a single PFG projection. Dose reconstructors should double the organ dose values in Table 3-6 when the records indicate that stereoscopic or stereo PFG was obtained on a worker. The stereo PFG was a technique in which two projections (i.e., two exposures) were obtained at slightly different X-ray tube angles. The physician then viewed the two projections with a stereoscope, which gave him a simulated three-dimensional view of the chest. The Hanford records have a blank line on the X-ray request form that indicates when stereo views were requested.

Table 3-6. Organ dose estimates for PFG until 1962.[a]

Organ	DCF 2.5 mm Al HVL[b] (mGy/Gy air kerma)	Organ dose (rem)[c]
Thyroid	174[d]	2.66E-01
Eye/brain	32[e]	4.90E-02
Ovaries[f]	N/A	6.85E-03
Urinary bladder[f]	N/A	6.85E-03
Colon/rectum[f]	N/A	6.85E-03
Testes[f]	N/A	4.80E-04
Lungs (male)	419	6.41E-01
Lungs (female)	451	6.90E-01
Thymus	451	6.90E-01
Esophagus	451	6.90E-01
Stomach	451	6.90E-01
Bone surface	451	6.90E-01
Liver/gall bladder/spleen	451	6.90E-01
Remainder	451	6.90E-01
Breast	49	7.50E-02
Uterus/embryo	1.3	1.99E-03
Bone marrow (male)	92	1.41E-01
Bone marrow (female)	86	1.32E-01
Entrance skin (EnSD)[g]	N/A	2.06E00

a. Based on measured entrance exposure of 1.53 R (Rising and Soldat 1959)
b. Dose Conversion Factors from Tables A.2 through A.8, ICRP Publication 34 (1982).
c. Dose reconstructors should double these organ doses when the records indicate stereo PFG.
d. Based on DCF for AP C-spine corrected for depth by 0.2 (ORAUT 2005).
e. Based on the DCF for the thyroid for the PA chest (ORAUT 2005).
f. Ovaries, testes, and associated analogue doses are based on measurements of 6.85 mrad for ovaries and 0.48 mrad for testes (Rising and Soldat 1959).
g. Entrance skin dose was determined by multiplying the entrance air kerma in air by the backscatter factor of 1.35 (for HVL of 2.5 mm Al) from NCRP Report No. 102 (1997), Table B-8.

The organ doses were determined by multiplying the measured entrance exposure value of 1.53 R (Rising and Soldat 1959) by DCFs in Tables A2 through A8 of ICRP 34 (ICRP 1982). These tables list DCFs based on an SID of 183 cm for conventional chest radiography. An SID of 40 inches or 102 cm was used for PFG (Rising and Soldat 1959). This difference in distance has a negligible effect on organ doses as discussed in ICRP Publication 34 (p. 23), and therefore, the values listed in Tables A2 to A8 are appropriate for PFG. An HVL of 2.5 mm Al was assumed for selection of the appropriate DCFs.

Because the SID for PFG is shorter than that for conventional radiography, the maximum size of the PFG beam is smaller than a poorly collimated beam at the 72 in. in conventional chest radiography. This affects the calculation of organ dose for several organs. For dose reconstruction, the PFG beam is assumed to include the thyroid, thoracic organs, and liver/gall bladder/spleen; the beam does not include the eye/brain, gonads, bladder, or colon/rectum. To ensure that the thyroid dose reflects the assumption that it is in the primary beam, the dose to the thyroid was determined using the DCF for the AP cervical spine (where the thyroid is definitely in the primary beam) and by correcting for the fact that the PFG chest projection was performed PA rather than AP (as is the case for the cervical spine projection). The correction consists of multiplying the DCF for the AP cervical spine by a depth dose correction factor of 20% (the approximate percentage depth dose at an assumed depth of the thyroid in the neck of 10 cm) (NCRP 1997; ORAUT 2005). The dose to the eye/brain is usually assumed to be the same as the dose to the thyroid (as shown in Table 3-5). However, as a result of the assumption that the PFG beam includes the thyroid but not the eye/brain, the dose to the

eye/brain is determined by using the larger of the DCFs for the thyroid for the PA skull or PA chest projections. The DCF for the thyroid dose from the PA chest projection is the larger of the two and was used to calculate the dose to the eye/brain for PFG.

The dose to the ovaries and testes are based not on the DCFs in ICRP Publication 34 (ICRP 1982), but on the measured doses in Rising and Soldat (1959), because these appear to be based on phantom measurements from the actual machine that was used in the screening of workers. The organ doses from PFG at Hanford are listed in Table 3-6. (Skin dose from all procedures are found in Tables 3-10 and 3-11 later in the document).

3.5.2 Radiography on 14- by 17-Inch Film

This section describes the calculation of organ doses for the various radiographic projections used at Hanford. Table 3-7 provides the organ DCFs for PA, LAT, and AP lordotic projections in three groups: (1) for 1944 to 1970 using 2.5 mm Al HVL, (2) for 1970 to 1990 using 2.5 mm Al HVL, and (3) for 1991 to the present using 4.0 mm Al HVLs.

3.5.2.1 PA Chest

The organ doses for the 14- by 17-in. chest X-rays are based on actual beam measurements by Rising and Soldat (1959) and WDOH (1990–1999). The measurements consist of entrance exposure measurements using average technique factors for PA chest X-rays and phantom measurements of gonad doses in 1959. Table 3-4 summarizes salient data for 14- by 17-in. PA chest radiography. The measurements from the State of Washington were rounded to whole years for simplicity.

Poor collimation is assumed before 1970, even though there is evidence that the X-ray machine at Kadlec Hospital in Richland had a Videx cone (Rising and Soldat 1959). A Videx cone had square double diaphragms and a small light for centering (Cahoon 1961), and it therefore had better capability for beam restriction than a standard circular cone. The assumption of poor collimation before 1970 affects the organ doses and the selection of some of the DCFs. To ensure that the thyroid dose reflects the assumption that it is in the primary beam of a poorly collimated PA chest projection, the dose to the thyroid was determined using the DCF for the AP cervical spine (where the thyroid is definitely in the primary beam) and corrected for the fact that the 14- by 17-in. conventional chest X-ray is PA rather than AP. The correction consists of multiplying the DCF for the AP cervical spine by a depth dose correction factor of 20% (the approximate percentage depth dose at an assumed depth of the thyroid in the neck of 10 cm) (NCRP 1997; ORAUT 2005). The dose to the eye/brain is usually assumed to be the same as the dose to the thyroid when collimation is good and both organs can be assumed to be outside the primary beam (as displayed in Table 3-5). However, as a result of the assumption that the X-ray beam before 1970 was poorly collimated, the beam is assumed to include the thyroid but not the eye/brain. The dose to the eye/brain was determined by using the larger of the DCFs for the thyroid for the PA skull or PA chest. The DCF for the thyroid dose from the PA chest is the larger of the two and was used to calculate the dose to the eye/brain for poorly collimated PA chest X-rays before 1970.

Dose reconstructors should multiply the PA chest doses by two if the records indicate that stereo views (two exposures) were taken. The claim records from Hanford appear to be fairly clear about this scenario. Dose reconstructors should also be aware that the administrative form that Hanford used to request the X-ray exams lists only “Chest AP” (as opposed to PA) as possible selections. This must be interpreted as an error on the form itself, as almost all chest X-rays are performed PA whenever possible [1]. On many of these records, the physician’s interpretation will list the exam correctly as “PA chest”.

3.5.2.2 Lateral Chest

The exposure necessary for a LAT 14- by 17-in. chest radiograph is greater than that for the more common PA chest projection. The entrance exposure must be increased because of the greater lateral body thickness in comparison to the PA thickness, which places the body closer to the X-ray tube. Few measurements are available for LAT 14- by 17-in. chest radiography at Hanford. Data indicate that the entrance air kerma in air from a LAT radiograph was 1.94 times the entrance air kerma in air from a PA chest radiograph (Kirklin et al. 1969). To ensure that exposure from this source was not underestimated, a moderately conservative factor of 2.5 was assumed for the ratio of entrance air kerma in air from LAT to PA chest radiographs for organ dose calculations.

Table 3-7. DCFs (mGy/Gy entrance kerma in air) for various chest projections.[a]

Organ	Projection	DCF through 1970 with 2.5 mm Al HVL	DCF 1971–1990 with 2.5 mm Al HVL	DCF 1991–present with 4.0 mm Al HVL
Thyroid	PA	174[b]	32	78
	LAT	137[c]	115	164
	AP Lordotic	868[d]	317	414
Eye brain	PA	32[e]	32	78
	LAT	137[c]	115	164
	AP Lordotic	868[d]	317	414
Ovaries	PA	N/A[f]	1.0	5.2
	LAT	N/A[g]	0.6	2.5
	AP Lordotic	233[h]	2.0	0.8
Testes	PA	N/A[f]	0.01	0.01
	LAT	N/A[f]	0.1	0.1
	AP Lordotic	18[h]	0.01	0.01
Lungs (male)	PA	419	419	628
	LAT	193	193	313
	AP Lordotic	473	473	685
Lungs (female)	PA	451	451	674
	LAT	220	220	351
	AP Lordotic	353[i]	353	536
Breast	PA	49	49	116
	LAT	255	255	343
	AP Lordotic	836	836	1004
Uterus	PA	N/A[f]	1.3	5.2
	LAT	N/A[f]	0.6	2.1
	AP Lordotic	305	1.5	4.9
Bone marrow (male)	PA	92	92	178
	LAT	37	37	76
	AP Lordotic	48	48	98
Bone marrow (female)	PA	86	86	172
	LAT	29	29	59
	AP Lordotic	48	48	97

a. DCFs from ICRP (1982, Tables A.2 to A.8).
b. DCF for AP cervical spine corrected for depth by 0.2 (ORAUT 2005).
c. DCF for LAT skull (ORAUT 2005).
d. DCF for AP cervical spine.
e. DCF for PA chest (ORAUT 2005).
f. Ovaries, testes, and associated analogue doses for the PA chest are based on measurements of 0.867 mrad for ovaries and 0.0293 mrad for testes (Rising and Soldat 1959).
g. Ovaries, testes, and associated analogue doses for the LAT chest are based on measurements of 0.867 mrad for ovaries and 0.0293 mrad for testes for the PA chest (Rising and Soldat 1959) and on the ratio of gonad dose from LAT chest to PA chest of 3 (Webster and Merrill 1957).
h. DCF for AP abdomen.
i. Note that the male lung DCF is higher than the female lung DCF for the AP projection.

Doses to the gonads, as previously mentioned, are based initially on phantom measurements by Rising and Soldat (1959). Rising and Soldat measured gonad dose for the PA chest projection but not for the LAT or the lordotic chest projections. To determine gonad dose for the LAT chest, the doses from Rising and Soldat were multiplied by 3, which is the ratio of the gonad dose from the LAT to the PA chest projection in Webster and Merrill (1957). Table 3-8 provides the organ doses for LAT 14- by 17-in. chest radiography.

Table 3-8. Organ doses (rem) for chest projections for all periods.[a,b]

Organ	Projection	1943-1959	1959–1970	1971–1982	1983–3/1990	1991–1997	1998–1999	1999–present
Thyroid	PA	1.37E-02	6.96E-03	1.28E-03	1.12E-03	1.64E-03	1.33E-03	8.58E-04
	Bucky PA			5.12E-03	4.48E-03			
	LAT/oblique	2.71E-02	1.37E-02	1.15E-02	1.01E-02	8.69E-03	7.05E-03	4.51E-03
	AP lordotic	6.86E-02	3.47E-02	1.27E-02	1.11E-02	8.69E-03	7.04E-03	4.55E-03
Eye/brain	PA	2.53E-03	1.28E-03	1.28E-03	1.12E-03	1.64E-03	1.33E-03	8.58E-04
	Bucky PA			5.12E-03	4.48E-03			
	LAT/oblique	2.71E-02	1.37E-02	1.15E-02	1.01E-02	8.69E-03	7.05E-03	4.51E-03
	AP lordotic	6.86E-02	3.47E-02	1.27E-02	1.11E-02	8.69E-03	7.04E-03	4.55E-03
Ovaries	PA	8.67E-04	8.67E-04	4.00E-05	3.50E-05	1.09E-04	8.84E-05	5.72E-05
	Bucky PA			1.60E-04	1.40E-04			
	LAT/oblique	2.06E-03	2.06E-03	6.00E-05	5.28E-05	1.33E-04	1.08E-04	6.88E-05
	AP lordotic	1.84E-02	9.32E-03	8.00E-05	7.00E-05	1.68E-05	1.36E-05	8.80E-06
Urinary/bladder	PA	8.67E-04	8.67E-04	4.00E-05	3.50E-05	1.09E-04	8.84E-05	5.72E-05
	Bucky PA			1.60E-04	1.40E-04			
	LAT/oblique	2.06E-03	2.06E-03	6.00E-05	5.28E-05	1.33E-04	1.08E-04	6.88E-05
	AP lordotic	1.84E-02	9.32E-03	8.00E-05	7.00E-05	1.68E-05	1.36E-05	8.80E-06
Colon/rectum	PA	8.67E-04	8.67E-04	4.00E-05	3.50E-05	1.09E-04	8.84E-05	5.72E-05
	Bucky PA			1.60E-04	1.40E-04			
	LAT/oblique	2.06E-03	2.06E-03	6.00E-05	5.28E-05	1.33E-04	1.08E-04	6.88E-05
	AP lordotic	1.84E-02	9.32E-03	8.00E-05	7.00E-05	1.68E-05	1.36E-05	8.80E-06
Testes	PA	2.93E-05	2.93E-05	4.00E-07	3.50E-07	2.10E-07	1.70E-07	1.10E-07
	Bucky PA			1.60E-06	1.40E-06			
	LAT/oblique	8.79E-05	8.79E-05	1.00E-05	8.80E-06	5.30E-06	4.30E-06	2.75E-06
	AP lordotic	1.42E-03	7.20E-04	4.00E-07	3.50E-07	2.10E-07	1.70E-07	1.10E-07
Lungs (male)	PA	3.31E-02	1.68E-02	1.68E-02	1.47E-02	1.32E-02	1.07E-02	6.91E-03
	Bucky PA			6.70E-02	5.87E-02			
	LAT/oblique	3.82E-02	1.93E-02	1.93E-02	1.70E-02	1.66E-02	1.35E-02	8.61E-03
	AP lordotic	3.74E-02	1.89E-02	1.89E-02	1.66E-02	1.44E-02	1.16E-02	7.54E-03
Lungs (female)	PA	3.56E-02	1.80E-02	1.80E-02	1.58E-02	1.42E-02	1.15E-02	7.41E-03
	Bucky PA			7.22E-02	6.31E-02			
	LAT/oblique	4.36E-02	2.20E-02	2.20E-02	1.94E-02	1.86E-02	1.51E-02	9.65E-03
	AP lordotic	2.79E-02	1.41E-02	1.41E-02	1.24E-02	1.13E-02	9.11E-03	5.90E-03
Thymus	PA	3.56E-02	1.80E-02	1.80E-02	1.58E-02	1.42E-02	1.15E-02	7.41E-03
	Bucky PA			7.22E-02	6.31E-02			
	LAT/oblique	4.36E-02	2.20E-02	2.20E-02	1.94E-02	1.86E-02	1.51E-02	9.65E-03
	AP lordotic	3.74E-02	1.89E-02	1.41E-02	1.24E-02	1.44E-02	1.16E-02	7.54E-03
Stomach	PA	3.56E-02	1.80E-02	1.80E-02	1.58E-02	1.42E-02	1.15E-02	7.41E-03
	Bucky PA			7.22E-02	6.31E-02			
	LAT/oblique	4.36E-02	2.20E-02	2.20E-02	1.94E-02	1.86E-02	1.51E-02	9.65E-03
	AP lordotic	3.74E-02	1.89E-02	1.41E-02	1.24E-02	1.44E-02	1.16E-02	7.54E-03

Organ	Projection	1943-1959	1959–1970	1971–1982	1983–3/1990	1991–1997	1998–1999	1999–present
Bone surface	PA	3.56E-02	1.80E-02	1.80E-02	1.58E-02	1.42E-02	1.15E-02	7.41E-03
	Bucky PA			7.22E-02	6.31E-02			
	LAT/oblique	4.36E-02	2.20E-02	2.20E-02	1.94E-02	1.86E-02	1.51E-02	9.65E-03
	AP lordotic	3.74E-02	1.89E-02	1.41E-02	1.24E-02	1.44E-02	1.16E-02	7.54E-03
Liver/gall bladder/spleen	PA	3.56E-02	1.80E-02	1.80E-02	1.58E-02	1.42E-02	1.15E-02	7.41E-03
	Bucky PA			7.22E-02	6.31E-02			
	LAT/oblique	4.36E-02	2.20E-02	2.20E-02	1.94E-02	1.86E-02	1.51E-02	9.65E-03
	AP lordotic	3.74E-02	1.89E-02	1.41E-02	1.24E-02	1.44E-02	1.16E-02	7.54E-03
Remainder organs	PA	3.56E-02	1.80E-02	1.80E-02	1.58E-02	1.42E-02	1.15E-02	7.41E-03
	Bucky PA			7.22E-02	6.31E-02			
	LAT/oblique	4.36E-02	2.20E-02	2.20E-02	1.94E-02	1.86E-02	1.51E-02	9.65E-03
	AP lordotic	3.74E-02	1.89E-02	1.41E-02	1.24E-02	1.44E-02	1.16E-02	7.54E-03
Breast	PA	3.87E-03	1.96E-03	1.96E-03	1.72E-03	2.44E-03	1.97E-03	1.28E-03
	Bucky PA			7.84E-03	6.86E-03			
	LAT/oblique	5.05E-02	2.55E-02	2.55E-02	2.24E-02	1.82E-02	1.47E-02	9.43E-03
	AP lordotic	6.60E-02	3.34E-02	3.34E-02	2.93E-02	2.11E-02	1.71E-02	1.10E-02
Uterus[a]	PA	8.67E-04	8.67E-04	5.20E-05	4.55E-05	1.09E-04	8.84E-05	5.72E-05
	Bucky PA			2.08E-04	1.82E-04			
	LAT/oblique	2.06E-03	2.06E-03	6.00E-05	5.28E-05	1.11E-04	9.03E-05	5.78E-05
	AP lordotic	2.41E-02	1.22E-02	6.00E-05	5.25E-05	1.03E-04	8.33E-05	5.39E-05
Bone marrow (male)	PA	7.27E-03	3.68E-03	3.68E-03	3.22E-03	3.74E-03	3.03E-03	1.96E-03
	Bucky PA			1.47E-02	1.29E-02			
	LAT/oblique	7.33E-03	3.70E-03	3.70E-03	3.26E-03	4.03E-03	3.27E-03	2.09E-03
	AP lordotic	3.79E-03	1.92E-03	1.92E-03	1.68E-03	2.06E-03	1.67E-03	1.08E-03
Bone marrow (female)	PA	6.79E-03	3.44E-03	3.44E-03	3.01E-03	3.61E-03	2.92E-03	1.89E-03
	Bucky PA			1.38E-02	1.20E-02			
	LAT/oblique	5.74E-03	2.90E-03	2.90E-03	2.55E-03	3.13E-03	2.54E-03	1.62E-03
	AP lordotic	3.79E-03	1.92E-03	1.92E-03	1.68E-03	2.04E-03	1.65E-03	1.07E-03
Entrance skin[c]	PA/AP	1.07E-01	5.40E-02	5.40E-02	4.70E-02	2.98E-02	2.41E-02	1.56E-02
	Bucky PA			2.16E-01	1.89E-01			
	LAT/oblique	2.67E-01	1.35E-01	1.35E-01	1.19E-01	7.53E-02	6.12E-02	3.90E-02

a. Doses before 1970 are based on measured values (Rising and Soldat 1959; Webster and Merrill 1957) for testes, ovaries, uterus, and analogues.
b. The LAT doses from this table can be used to determine the dose from oblique projections when claim file records show they were provided.
c. Entrance skin dose is determined by multiplying the entrance air kerma by the backscatter factors of 1.35 and 1.42 for HVL of 2.5 mm Al and 4.0 mm Al, respectively, from NCRP Report 102 (NRCP 1997, Table B-8). Skin doses for all areas of skin are provided in Tables 3-10 and 3-11.

3.5.2.3 Bucky PA Chest

Some of the claim file records from the 1970s and 1980s indicate that a special four-projection chest series, including the "Bucky PA Chest" projection was performed on some of the workers. It appears that this series was taken on workers who were suspected of having early signs of asbestosis or who worked with asbestos. *Bucky* is a term for a reciprocating grid, which consists of fine lead strips that are placed in front of the film that move back and forth during the exposure. The purpose of the grid is to absorb some of the scatter radiation that is emitted at large oblique angles from reaching the film. Such obliquely scattered radiation obscures detail in the image and detracts from it. The fact that a specific request is recorded for the grid to be used implies that the grid was not used for PA chest X-rays routinely during that period. After 1990, the State of Washington Department of Health measurements indicate that a grid was used for all PA chests (WDOH 1990–1999). Therefore, the Bucky PA doses are only provided for 1971 to 1990.

Because the grid itself consists of radiation absorbing material, the exposure factors must be increased when the grid is used. Table B-4 of NCRP Report 102, gives a bucky factor (the factor by which the exposure must be increased) of about 4.0 for 80 kVp and a 10:1 or 12:1 ratio grid (NCRP 1997), while Cahoon (1961, p. 131) gives a factor of 3. The entrance air kerma in air values were therefore multiplied by 4 while using the same DCFs to obtain the organ doses for the Bucky PA projection. These organ doses are listed in Table 3-8.

3.5.2.4 Oblique Chest

Part of the special four-projection chest series included two oblique projections of the chest. These are assumed to be the right posterior oblique (RPO) and the left posterior oblique (LPO) without evidence to the contrary. The position of the body for the oblique projection is similar but not identical to the position of the body for the LAT chest projection. The oblique chest projections would therefore have required similar technique factors of kVp, milliampere-seconds, and SID as the LAT projection because the chest thickness would be similar. For dose reconstruction, the organ doses from the LAT projection in Table 3-8 can be used for the oblique projection. Skin doses for the oblique projections are provided separately in Tables 3-10 and 3-11. It should be noted that the skin doses are not identical to the LAT chest skin doses because of the different position of the body relative to the direction of the X-ray beam. The doses in the tables are for the RPO and LPO. The Hanford claim records indicate that when oblique chest projections were done, both oblique projections were done, and so dose reconstructors should include the dose from both.

3.5.2.5 Lordotic Chest

The lordotic projection was commonly performed as AP, in which the worker faced the X-ray tube and leaned back from the waist towards the cassette for the exposure (Ballinger 1982). Organ doses from the lordotic projection are in Table 3-8. Because the lordotic projection is performed as AP, the gonad doses were determined by using the DCFs for the AP abdomen and assuming that the X-ray beam was poorly collimated and the gonads were in the primary beam.

It is worth noting that in the PA chest projection the DCF for the female lung is higher than that for the male lung, but in the lordotic chest projection performed as AP the DCF is higher for the male lung. Therefore, the male lung dose value is used for the organs in IREP without specific ICRP Publication 34 DCFs (such as the esophagus, stomach, etc.; ICRP 1982) when usually the female lung dose value is used for these organs (see Table 3-4). Organ doses for the lordotic projection are not provided after 1990 because the records do not indicate that this projection was used after that date.

3.5.3 Skin Doses

The skin doses from all chest projections and all periods were developed in accordance with the general scheme in ORAUT-OTIB-0006 (ORAUT 2005), but have been expanded to include the chest projections in the Hanford claim files (i.e., AP lordotic, RPO, and LPO). The scheme defines areas of skin as belonging to one of the following categories for dose assignment: entrance skin dose (EnSD), exit skin dose (ExSD), outside but near the primary beam entrance (10% EnSD), outside but near the primary beam exit (10% ExSD), and remote skin dose (RSD). The skin dose categories are listed in Table 3-9. The category for a particular area of skin depends on the chest projection because of the different exposure geometries and on the size of the beam (poor collimation is assumed before 1970). The skin doses from all projections are provided in Tables 3-10 and 3-11.

3.6 UNCERTAINTY ANALYSIS FOR HANFORD RADIOGRAPHY DOSES

Error (deviation from the correct, true, or conventionally accepted value of a quantity) and uncertainty (potential range of a stated, measured, assumed, or otherwise determined value of a quantity) provide an indication of the confidence 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 the confidence level (e.g., a 99% confidence level indicates that the correct or true value, although not actually known, has a 99% probability of falling within the cited range). Uncertainty includes both precision (reproducibility of the measurement) and accuracy (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, because X-ray doses at Hanford were derived largely from actual beam intensity measurements, in practice only five variables can be reasonably considered to have an impact on dose uncertainty:

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

The influence of other factors such as use of screens, grids, reciprocity failure, film speed, and development, while potentially variable, are in a sense included among these five variables because the beam output intensity measurements at Hanford were based on the actual technique factors for the existing conditions.

The actual beam measurements at Hanford were made with R-meters or similar ionization chamber devices. If they were properly calibrated and used, they typically and historically had an uncertainty of ±2% for photon energies below 400 keV (Kathren and Larson 1969). Although more recent versions of these instruments might provide a somewhat smaller uncertainty [perhaps on the order of ±1% (NBS 1985; Lamperti, Loftus, and Loevenger 1988)], for conservatism the uncertainty range of ±2% should be applied to measurements of X-ray intensity at Hanford.

For a given set of machine settings and parameters, X-ray output is theoretically constant. In general, for a given kVp setting, variation in kVp falls within ±5% of the machine setting (Seibert et al. 1991). As noted above, beam intensity is approximately proportional to the 1.7 power of the kilovoltage; this translates to an uncertainty of approximately ±8.6% in relation to output beam intensity in the 80 to 100 kVp that was used for radiography at Hanford. For conservatism, this is rounded up to ±9%.

Table 3-9. Skin dose guidance for various chest projections and periods.

Area of skin	PFG 1943–about 1962	PA before 1970	LAT before 1970	AP lordotic before 1970	RPO before 1970	LPO before 1970	PA after 1970	LAT after 1970	AP lordotic after 1970	RPO after 1970	LPO after 1970
Right front shoulder	ExSD	ExSD	EnSD	EnSD	ExSD	ExSD	ExSD	EnSD	EnSD	ExSD	ExSD
Right back shoulder	EnSD	EnSD	EnSD	ExSD	EnSD	EnSD	EnSD	EnSD	ExSD	EnSD	EnSD
Left front shoulder	ExSD	ExSD	ExSD	EnSD	ExSD	ExSD	ExSD	ExSD	EnSD	ExSD	ExSD
Left back shoulder	EnSD	EnSD	ExSD	ExSD	EnSD	EnSD	EnSD	ExSD	ExSD	EnSD	EnSD
Right upper arm to elbow	10% EnSD	EnSD	EnSD	EnSD	EnSD	EnSD	10% EnSD	EnSD	EnSD	10% EnSD	10% EnSD
Left upper arm to elbow	10% EnSD	EnSD	ExSD	EnSD	EnSD	EnSD	10% EnSD	ExSD	EnSD	10% EnSD	10% EnSD
Left hand	EnSD	EnSD	10% EnSD	10% EnSD	10% EnSD	10% EnSD	10% EnSD	10% EnSD	10% EnSD	10% EnSD	10% EnSD
Right hand	EnSD	EnSD	10% EnSD	10% EnSD	10% EnSD	10% EnSD	10% EnSD	10% EnSD	10% EnSD	10% EnSD	10% EnSD
Left elbow, forearm, wrist	10% EnSD	EnSD	10% EnSD	EnSD	10% EnSD	10% EnSD	10% EnSD	10% EnSD	EnSD	10% EnSD	10% EnSD
Right elbow, forearm, wrist	10% EnSD	EnSD	10% EnSD	EnSD	10% EnSD	10% EnSD	10% EnSD	10% EnSD	EnSD	10% EnSD	10% EnSD
Right side of head (including ear)	10% EnSD	10% EnSD	Eye/brain	10% EnSD	10% ExSD	10% EnSD	10% EnSD	10% EnSD	10% EnSD	10% ExSD	10% EnSD
Left side of head including ear	10% EnSD	10% EnSD	Eye/brain	10% EnSD	10% EnSD	10% ExSD	10% EnSD	10% EnSD	10% EnSD	10% EnSD	10% ExSD
Front left thigh	RSD (0.52 m)	RSD (0.52 m)	RSD (0.52 m)	RSD (0.52 m)	RSD (0.52 m)	RSD (0.52 m)	RSD (0.52 m)	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)	RSD (0.52 m)	RSD (0.52 m)	RSD (0.52 m)	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)	RSD (0.52 m)	RSD (0.52 m)	RSD (0.52 m)	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)	RSD (0.52 m)	RSD (0.52 m)	RSD (0.52 m)	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)	RSD (0.86 m)	RSD (0.86 m)	RSD (0.86 m)	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)	RSD (0.86 m)	RSD (0.86 m)	RSD (0.86 m)	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	EnSD	EnSD	ExSD	Eye/brain	10% EnSD	EnSD	10% EnSD	10% ExSD
Right side of face	Eye/brain	Eye/brain	Eye/brain	EnSD	ExSD	EnSD	Eye/brain	10% EnSD	EnSD	10% ExSD	10% EnSD
Left side of neck	10% EnSD	EnSD	Eye/brain	EnSD	EnSD	ExSD	10% EnSD	10% EnSD	EnSD	10% EnSD	10% ExSD
Right side of neck	10% EnSD	EnSD	Eye/brain	EnSD	ExSD	EnSD	10% EnSD	10% EnSD	EnSD	10% ExSD	10% EnSD
Back of head	10% EnSD	10% EnSD	Eye/brain	ExSD	10% EnSD	10% EnSD	10% EnSD	10% EnSD	ExSD	10% EnSD	10% EnSD
Front of neck	Eye/brain	Eye/brain	Eye/brain	EnSD	Eye/brain	Eye/brain	Thyroid	10% EnSD	EnSD	Thyroid	Thyroid
Back of neck	10% EnSD	EnSD	Eye/brain	ExSD	EnSD	EnSD	10% EnSD	10% EnSD	ExSD	10% EnSD	10% EnSD
Front torso: base of neck to end of sternum	ExSD	ExSD	Lung	EnSD	ExSD	ExSD	ExSD	Lung	EnSD	ExSD	ExSD
Front torso: end of sternum to lowest rib	ExSD	ExSD	Lung	EnSD	ExSD	ExSD	ExSD	Lung	EnSD	ExSD	ExSD
Front torso: lowest rib to iliac crest	ExSD	ExSD	Lung	EnSD	ExSD	ExSD	10% ExSD	10% Lung	EnSD	10% ExSD	10% ExSD
Front torso: iliac crest to pubis	10% ExSD	10% ExSD	10% Lung	10% EnSD	10% ExSD	10% ExSD	10% ExSD	10% Lung	10% EnSD	10% ExSD	10% ExSD

Back torso: base of neck to mid-back	EnSD	EnSD	Lung	ExSD	EnSD	EnSD	EnSD	Lung	ExSD	EnSD	EnSD
Back torso: mid-back to lowest rib	EnSD	EnSD	Lung	ExSD	EnSD	EnSD	EnSD	Lung	ExSD	EnSD	EnSD
Back torso: lowest rib to iliac crest	EnSD	EnSD	Lung	ExSD	EnSD	EnSD	10% EnSD	10% Lung	ExSD	10% EnSD	10% EnSD
Back torso: buttocks (Iliac crest and below)	10% EnSD	10% EnSD	10% Lung	10% ExSD	10% EnSD	10% EnSD	10% EnSD	10% Lung	10% ExSD	10% EnSD	10% EnSD
Right torso: base of neck to end of sternum	EnSD	EnSD	EnSD	EnSD	ExSD	EnSD	EnSD	EnSD	EnSD	ExSD	EnSD
Right torso: end of sternum to lowest rib	EnSD	EnSD	EnSD	EnSD	ExSD	EnSD	EnSD	EnSD	EnSD	ExSD	EnSD
Right torso: lowest rib to iliac crest	EnSD	EnSD	EnSD	EnSD	ExSD	EnSD	10% EnSD	10% EnSD	EnSD	10% ExSD	10% EnSD
Right torso: iliac crest to pubis (right hip)	10% EnSD	10% EnSD	10% EnSD	10% EnSD	10% ExSD	10% EnSD	10% EnSD	10% EnSD	10% EnSD	10% ExSD	10% EnSD
Left torso: base of neck to end of sternum	EnSD	EnSD	ExSD	EnSD	EnSD	ExSD	EnSD	ExSD	EnSD	EnSD	ExSD
Left torso: end of sternum to lowest rib	EnSD	EnSD	ExSD	EnSD	EnSD	ExSD	EnSD	ExSD	EnSD	EnSD	ExSD
Left torso: lowest rib to iliac crest	EnSD	EnSD	ExSD	EnSD	EnSD	ExSD	10% EnSD	10% ExSD	EnSD	10% EnSD	10% ExSD
Left torso: iliac crest to pubis (left hip)	10% EnSD	10% EnSD	10% ExSD	10% EnSD	10% EnSD	10% ExSD	10% EnSD	10% ExSD	10% EnSD	10% EnSD	10% ExSD

Table 3-10. Skin dose (rem) from various chest projections, 1943 to 1982.[a]

Area of skin	PFG 1943–1962	1943-1959	LAT Until 1959	AP lordotic Until 1959	PA 1959–1970	LAT 1959–1970	AP lordotic 1959–1970	PA 1971–1982	LAT 1971–1982	AP lordotic 1971–1982	Bucky PA 1971–1982	RPO 1971–1982	LPO 1971–1982
Right front shoulder	4.49E-02	2.3E-03	2.67E-01	1.07E-01	1.2E-03	1.35E-01	5.40E-02	1.2E-03	1.35E-01	5.40E-02	4.7E-03	6E-04	6E-04
Right back shoulder	2.06E+00	1.07E-01	2.67E-01	2.3E-03	5.40E-02	1.35E-01	1.2E-03	5.40E-02	1.35E-01	1.2E-03	2.16E-01	1.35E-01	1.35E-01
Left front shoulder	4.49E-02	2.3E-03	1.2E-03	1.07E-01	1.2E-03	6E-04	5.40E-02	1.2E-03	6E-04	5.40E-02	4.7E-03	6E-04	6E-04
Left back shoulder	2.06E+00	1.07E-01	1.2E-03	2.3E-03	5.40E-02	6E-04	1.2E-03	5.40E-02	6E-04	1.2E-03	2.16E-01	1.35E-01	1.35E-01
Right upper arm to elbow	2.06E-01	1.07E-01	2.67E-01	1.07E-01	5.40E-02	1.35E-01	5.40E-02	5.4E-03	1.35E-01	5.40E-02	2.16E-02	1.35E-01	1.35E-01
Left upper arm to elbow	2.06E-01	1.07E-01	1.2E-03	1.07E-01	5.40E-02	5.9E-04	5.40E-02	5.4E-03	6E-04	5.40E-02	2.16E-02	1.35E-01	1.35E-01
Left hand	2.06E+00	1.07E-01	2.67E-02	1.07E-02	5.40E-02	1.35E-02	5.4E-03	5.4E-03	1.35E-02	5.4E-03	2.16E-02	1.35E-02	1.35E-02
Right hand	2.06E+00	1.07E-01	2.67E-02	1.07E-02	5.40E-02	1.35E-02	5.4E-03	5.4E-03	1.35E-02	5.4E-03	2.16E-02	1.35E-02	1.35E-02
Left elbow, forearm, wrist	2.06E-01	1.07E-01	2.67E-02	1.07E-01	5.40E-02	1.35E-02	5.40E-02	5.4E-03	1.35E-02	5.40E-02	2.16E-02	1.35E-02	1.35E-02
Right elbow, forearm, wrist	2.06E-01	1.07E-01	2.67E-02	1.07E-01	5.40E-02	1.35E-02	5.40E-02	5.4E-03	1.35E-02	5.40E-02	2.16E-02	1.35E-02	1.35E-02
Right side of head including ear	2.06E-01	1.07E-02	2.71E-02	1.07E-02	5.4E-03	1.37E-02	5.4E-03	5.4E-03	1.35E-02	5.4E-03	2.16E-02	6E-05	1.35E-02
Left side of head including ear	2.06E-01	1.07E-02	2.71E-02	1.07E-02	5.4E-03	1.37E-02	5.4E-03	5.4E-03	1.35E-02	5.4E-03	2.16E-02	1.35E-02	6E-05
Front left thigh	5E-04	3E-05	4E-05	3E-05	2E-05	2E-05	2E-05	2E-05	2E-05	2E-05	6E-05	2E-05	2E-05
Back left thigh	5E-04	3E-05	4E-05	3E-05	2E-05	2E-05	2E-05	2E-05	2E-05	2E-05	6E-05	2E-05	2E-05
Front right thigh	5E-04	3E-05	4E-05	3E-05	2E-05	2E-05	2E-05	2E-05	2E-05	2E-05	6E-05	2E-05	2E-05
Back right thigh	5E-04	3E-05	4E-05	3E-05	2E-05	2E-05	2E-05	2E-05	2E-05	2E-05	6E-05	2E-05	2E-05
Left knee and below	2E-04	1E-05	1E-05	1E-05	6E-06	8E-06	6E-06	6E-06	8E-06	6E-06	2E-05	8E-06	8E-06
Right knee and below	2E-04	1E-05	1E-05	1E-05	6E-06	8E-06	6E-06	6E-06	8E-06	6E-06	2E-05	8E-06	8E-06
Left side of face	4.90E-02	2.5E-03	2.71E-02	1.07E-01	1.3E-03	1.37E-02	5.40E-02	1.3E-03	1.35E-02	5.40E-02	5.1E-03	1.35E-01	6E-04
Right side of face	4.90E-02	2.5E-03	2.71E-02	1.07E-01	1.3E-03	1.37E-02	5.40E-02	1.3E-03	1.35E-02	5.40E-02	5.1E-03	6E-04	1.35E-01
Left side of neck	2.06E-01	1.07E-01	2.71E-02	1.07E-01	5.40E-02	1.37E-02	5.40E-02	5.4E-03	1.35E-02	5.40E-02	2.16E-02	1.35E-01	6E-04
Right side of neck	2.06E-01	1.07E-01	2.71E-02	1.07E-01	5.40E-02	1.37E-02	5.40E-02	5.4E-03	1.35E-02	5.40E-02	2.16E-02	6E-04	1.35E-01
Back of head	2.06E-01	1.07E-02	2.71E-02	2.3E-03	5.4E-03	1.37E-02	1.2E-03	5.4E-03	1.35E-02	1.2E-03	2.16E-02	1.35E-02	1.35E-02
Front of neck	4.90E-02	2.5E-03	2.71E-02	1.07E-01	1.3E-03	1.37E-02	5.40E-02	1.3E-03	1.35E-02	5.40E-02	5.1E-03	1.15E-02	1.15E-02
Back of neck	2.06E-01	1.07E-01	2.71E-02	2.3E-03	5.40E-02	1.37E-02	1.2E-03	5.4E-03	1.35E-02	1.2E-03	2.16E-02	1.35E-01	1.35E-01
Front torso: base of neck to end of sternum	4.49E-02	2.3E-03	4.36E-02	1.07E-01	1.2E-03	2.20E-02	5.40E-02	1.2E-03	2.20E-02	5.40E-02	4.7E-03	6E-04	6E-04
Front torso: end of sternum to lowest rib	4.49E-02	2.3E-03	4.36E-02	1.07E-01	1.2E-03	2.20E-02	5.40E-02	1.2E-03	2.20E-02	5.40E-02	4.7E-03	6E-04	6E-04
Front torso: lowest rib to iliac crest	4.49E-02	2.3E-03	4.36E-02	1.07E-01	1.2E-03	2.20E-02	5.40E-02	1E-04	2.2E-03	5.40E-02	5E-04	6E-04	6E-04
Front torso: iliac crest to pubis	4.49E-03	2E-04	4.4E-03	1.07E-02	1E-04	2.2E-03	5.4E-03	1E-04	2.2E-03	5.4E-03	5E-04	6E-05	6E-05
Back torso: base of neck to mid-back	2.06E+00	1.07E-01	4.36E-02	2.3E-03	5.40E-02	2.20E-02	1.2E-03	5.40E-02	2.20E-02	1.2E-03	2.16E-01	1.35E-01	1.35E-01
Back torso: mid-back to lowest rib	2.06E+00	1.07E-01	4.36E-02	2.3E-03	5.40E-02	2.20E-02	1.2E-03	5.40E-02	2.20E-02	1.2E-03	2.16E-01	1.35E-01	1.35E-01
Back torso: lowest rib to iliac crest	2.06E+00	1.07E-01	4.36E-02	2.3E-03	5.40E-02	2.20E-02	1.2E-03	5.4E-03	2.2E-03	1.2E-03	2.16E-02	1.35E-01	1.35E-01
Back torso: buttocks (Iliac crest and below)	2.06E-01	1.07E-02	4.4E-03	2.E-04	5.4E-03	2.2E-03	1E-04	5.4E-03	2.2E-03	1E-04	2.16E-02	1.35E-02	1.35E-02
Right torso: base of neck to end of sternum	2.06E+00	1.07E-01	2.67E-01	1.07E-01	5.40E-02	1.35E-01	5.40E-02	5.40E-02	1.35E-01	5.40E-02	2.16E-01	6E-04	1.35E-01

Area of skin	PFG 1943–1962	1943-1959	LAT Until 1959	AP lordotic Until 1959	PA 1959–1970	LAT 1959–1970	AP lordotic 1959–1970	PA 1971–1982	LAT 1971–1982	AP lordotic 1971–1982	Bucky PA 1971–1982	RPO 1971–1982	LPO 1971–1982
Right torso: end of sternum to lowest rib	2.06E+00	1.07E-01	2.67E-01	1.07E-01	5.40E-02	1.35E-01	5.40E-02	5.40E-02	1.35E-01	5.40E-02	2.16E-01	6E-04	1.35E-01
Right torso: lowest rib to iliac crest	2.06E+00	1.07E-01	2.67E-01	1.07E-01	5.40E-02	1.35E-01	5.40E-02	5.4E-03	1.35E-02	5.40E-02	2.16E-02	6E-04	1.35E-01
Right torso: iliac crest to pubis (right hip)	2.06E-01	1.07E-02	2.67E-02	1.07E-02	5.4E-03	1.35E-02	5.4E-03	5.4E-03	1.35E-02	5.4E-03	2.16E-02	6E-05	1.35E-02
Left torso: base of neck to end of sternum	2.06E+00	1.07E-01	1.2E-03	1.07E-01	5.40E-02	6E-04	5.40E-02	5.40E-02	6E-04	5.40E-02	2.16E-01	1.35E-01	6E-04
Left torso: end of sternum to lowest rib	2.06E+00	1.07E-01	1.2E-03	1.07E-01	5.40E-02	6E-04	5.40E-02	5.40E-02	6E-04	5.40E-02	2.16E-01	1.35E-01	6E-04
Left torso: lowest rib to iliac crest	2.06E+00	1.07E-01	1.2E-03	1.07E-01	5.40E-02	6E-04	5.40E-02	5.4E-03	6E-05	5.40E-02	2.16E-02	1.35E-01	6E-04
Left torso: iliac crest to pubis (Left hip)	2.06E-01	1.07E-02	1E-04	1.07E-02	5.4E-03	6E-05	5.4E-03	5.4E-03	6E-05	5.4E-03	2.16E-02	1.35E-02	6E-05

a. Values less than 1 mrem shown to one significant digit.

Table 3-11. Skin dose (rem) from various chest projections, 1983 to present.[a]

Area of skin	PA 1983–1990	LAT 1983–1990	AP Lordotic 1983–1990	Bucky PA 1983–1990	RPO 1983–1990	LPO 1983–1990	PA 1991–1997	LAT 1991–1997	PA 1998–1999	LAT 1998–1999	PA 1999–present	LAT 1999–present
Right front shoulder	1.0E-03	1.19E-01	4.70E-02	4.1E-03	5E-04	5E-04	1.0E-03	7.53E-02	8.E-04	6.12E-02	5E-04	3.90E-02
Right back shoulder	4.70E-02	1.19E-01	1.0E-03	1.89E-01	1.19E-01	1.19E-01	2.98E-02	7.53E-02	2.41E-02	6.12E-02	1.56E-02	3.90E-02
Left front shoulder	1.0E-03	5E-04	4.70E-02	4.1E-03	5E-04	5E-04	1.0E-03	6E-04	8E-04	5E-04	5E-04	3E-04
Left back shoulder	4.70E-02	5E-04	1.0E-03	1.89E-01	1.19E-01	1.19E-01	2.98E-02	6E-04	2.41E-02	5E-04	1.56E-02	3E-04
Right upper arm to elbow	4.7E-03	1.19E-01	4.70E-02	1.89E-02	1.19E-01	1.19E-01	3.0E-03	7.53E-02	2.4E-03	6.12E-02	1.6E-03	3.90E-02
Left upper arm to elbow	4.7E-03	5.2E-04	4.70E-02	1.89E-02	1.19E-01	1.19E-01	3.0E-03	6.E-04	2.4E-03	5E-04	1.6E-03	3E-04
Left hand	4.7E-03	1.19E-02	4.7E-03	1.89E-02	1.19E-02	1.19E-02	3.0E-03	7.5E-03	2.4E-03	6.1E-03	1.6E-03	3.9E-03
Right hand	4.7E-03	1.19E-02	4.7E-03	1.89E-02	1.19E-02	1.19E-02	3.0E-03	7.5E-03	2.4E-03	6.1E-03	1.6E-03	3.9E-03
Left elbow, forearm, wrist	4.7E-03	1.19E-02	4.70E-02	1.89E-02	1.19E-02	1.19E-02	3.0E-03	7.5E-03	2.4E-03	6.1E-03	1.6E-03	3.9E-03
Right elbow, forearm, wrist	4.7E-03	1.19E-02	4.70E-02	1.89E-02	1.19E-02	1.19E-02	3.0E-03	7.5E-03	2.4E-03	6.1E-03	1.6E-03	3.9E-03
Right side of head including ear	4.7E-03	1.19E-02	4.7E-03	1.89E-02	5E-05	1.19E-02	3.0E-03	7.5E-03	2.4E-03	6.1E-03	1.6E-03	3.9E-03
Left side of head including ear	4.7E-03	1.19E-02	4.7E-03	1.89E-02	1.19E-02	5E-05	3.0E-03	7.5E-03	2.4E-03	6.1E-03	1.6E-03	3.9E-03
Front left thigh	1E-05	2E-05	1E-05	5E-05	2E-05	2E-05	1E-05	2E-05	9E-06	1E-05	6E-06	8E-06
Back left thigh	1E-05	2E-05	1E-05	5E-05	2E-05	2E-05	1E-05	2E-05	9E-06	1E-05	6E-06	8E-06
Front right thigh	1E-05	2E-05	1E-05	5E-05	2E-05	2E-05	1E-05	2E-05	9E-06	1E-05	6E-06	8E-06
Back right thigh	1E-05	2E-05	1E-05	5E-05	2E-05	2E-05	1E-05	2E-05	9E-06	1E-05	6E-06	8E-06
Left knee and below	5E-06	7E-06	5E-06	2E-05	7E-06	7E-06	4E-06	6E-06	3E-06	5E-06	2E-06	3E-06
Right knee and below	5E-06	7E-06	5E-06	2E-05	7E-06	7E-06	4E-06	6E-06	3E-06	5E-06	2E-06	3E-06
Left side of face	1.01E-02	1.19E-02	4.70E-02	1.01E-02	1.19E-01	5E-04	1.6E-03	7.5E-03	1.3E-03	6.1E-03	9E-04	3.9E-03
Right side of face	1.01E-02	1.19E-02	4.70E-02	1.01E-02	5E-04	1.19E-01	1.6E-03	7.5E-03	1.3E-03	6.1E-03	9E-04	3.9E-03
Left side of neck	4.7E-03	1.19E-02	4.70E-02	1.89E-02	1.19E-01	5E-04	3.0E-03	7.5E-03	2.4E-03	6.1E-03	1.6E-03	3.9E-03
Right side of neck	4.7E-03	1.19E-02	4.70E-02	1.89E-02	5E-04	1.19E-01	3.0E-03	7.5E-03	2.4E-03	6.1E-03	1.6E-03	3.9E-03
Back of head	4.7E-03	1.19E-02	1.0E-03	1.89E-02	1.19E-02	1.19E-02	3.0E-03	7.5E-03	2.4E-03	6.1E-03	1.6E-03	3.9E-03
Front of neck	1.01E-02	1.19E-02	4.70E-02	1.01E-02	1.01E-02	1.01E-02	1.6E-03	7.5E-03	1.3E-03	6.1E-03	9E-04	3.9E-03
Back of neck	4.7E-03	1.19E-02	1.0E-03	1.89E-02	1.19E-01	1.19E-01	3.0E-03	7.5E-03	2.4E-03	6.1E-03	1.6E-03	3.9E-03
Front torso: base of neck to end of sternum	1.0E-03	1.94E-02	4.70E-02	4.1E-03	5E-04	5E-04	1.0E-03	1.86E-02	8E-04	1.51E-02	5E-04	9.7E-03
Front torso: end of sternum to lowest rib	1.0E-03	1.94E-02	4.70E-02	4.1E-03	5E-04	5E-04	1.0E-03	1.86E-02	8E-04	1.51E-02	5E-04	9.7E-03
Front torso: lowest Rib to iliac crest	1E-04	1.9E-03	4.70E-02	4E-04	5E-04	5E-04	1E-04	1.9E-03	8E-05	1.5E-03	5E-05	1E-03
Front torso: iliac crest to pubis	1E-04	1.9E-03	4.7E-03	4E-04	5E-05	5E-05	1E-04	1.9E-03	8E-05	1.5E-03	5E-05	1E-03
Back torso: base of neck to mid-back	4.70E-02	1.94E-02	1.0E-03	1.89E-01	1.19E-01	1.19E-01	2.98E-02	1.86E-02	2.41E-02	1.51E-02	1.56E-02	9.7E-03
Back torso: mid-back to lowest rib	4.70E-02	1.94E-02	1.0E-03	1.89E-01	1.19E-01	1.19E-01	2.98E-02	1.86E-02	2.41E-02	1.51E-02	1.56E-02	9.7E-03
Back torso: lowest rib to iliac crest	4.7E-03	1.9E-03	1.0E-03	1.89E-02	1.19E-01	1.19E-01	3.0E-03	1.9E-03	2.4E-03	1.5E-03	1.6E-03	1E-03
Back torso: buttocks (Iliac crest and below)	4.7E-03	1.9E-03	1E-04	1.89E-02	1.19E-02	1.19E-02	3.0E-03	1.9E-03	2.4E-03	1.5E-03	1.6E-03	1E-03
Right torso: base of neck to end of sternum	4.70E-02	1.19E-01	4.70E-02	1.89E-01	5E-04	1.19E-01	2.98E-02	7.53E-02	2.41E-02	6.12E-02	1.56E-02	3.90E-02
Right torso: end of sternum to lowest rib	4.70E-02	1.19E-01	4.70E-02	1.89E-01	5E-04	1.19E-01	2.98E-02	7.53E-02	2.41E-02	6.12E-02	1.56E-02	3.90E-02
Right torso: lowest rib to iliac crest	4.7E-03	1.19E-02	4.70E-02	1.89E-02	5E-04	1.19E-01	3.0E-03	7.5E-03	2.4E-03	6.1E-03	1.6E-03	3.9E-03
Right torso: iliac crest to pubis (right hip)	4.7E-03	1.19E-02	4.7E-03	1.89E-02	5E-05	1.19E-02	3.0E-03	7.5E-03	2.4E-03	6.1E-03	1.6E-03	3.9E-03
Left torso: base of neck to end of sternum	4.70E-02	5E-04	4.70E-02	1.89E-01	1.19E-01	5E-04	2.98E-02	6E-04	2.41E-02	5E-04	1.56E-02	3E-04
Left torso: end of sternum to lowest rib	4.70E-02	5E-04	4.70E-02	1.89E-01	1.19E-01	5E-04	2.98E-02	6E-04	2.41E-02	5E-04	1.56E-02	3E-04
Left torso: lowest rib to iliac crest	4.7E-03	5E-05	4.70E-02	1.89E-02	1.19E-01	5E-04	3.0E-03	6E-05	2.4E-03	5E-05	1.6E-03	3E-05
Left torso: iliac crest to pubis (left hip)	4.7E-03	5E-05	4.7E-03	1.89E-02	1.19E-02	5E-05	3.0E-03	6E-05	2.4E-03	5E-05	1.6E-03	3E-05

a. Values less than 1 mrem shown to one significant digit.

Similarly, slight variations in tube current are normal; as a tube ages or heats up from use, current can change and typically drops. With all other factors constant, beam intensity reduces in direct proportion to the change in tube current. The reduction in beam output from current variation is typically not more than a few percent under normal operating conditions; large decreases are readily detectable and result in maintenance on the machine to restore the output or, as a temporary measure, an increase in the current or kilovoltage to provide the necessary intensity for proper film density. There is no evidence to suggest that such temporary measures were ever necessary or applied at Hanford. For a given kilovoltage 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; there might be minor changes in output as the tube heats from normal use. Because these variations are typically small, the estimated uncertainty in beam output attributable to current variation is ±5%.

Another parameter that has potential to affect the dose from radiography, perhaps significantly, relates to the time of exposure. A full-wave rectified machine produces 120 pulses per second of X-rays. In an 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 ±17%. For an exposure time of 1/30 of a second, the change in output corresponding to a deviation of ±1 pulse is ±25%. Early mechanical timers were notoriously inaccurate; accuracy improved significantly with the introduction of electronic timers. Other than measurements of reproducibility made in the late 1980s and beyond by the State of Washington, there are no data on which to base an evaluation of the accuracy and precision of the timers on Hanford X-ray machines. The measurements made by the State suggest that the timers, and indeed the entire X-ray output, were fairly constant (WDOH 1990–1999). However, for conservatism, the assumed uncertainty in beam output attributable to timers has an upper limit of ±25%.

The final factor likely to affect worker dose relates to distance from the source of the X-rays, which is a determinant of the entrance air kerma in air. For a given individual, the SSD is determined largely by the body thickness of the worker and the accuracy of the positioning. 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 does not report the measured chest thicknesses for these nine workers, the entrance skin doses are reported and reflect the increase in exposure needed to radiograph thicker body parts, in this case, chests. The standard uncertainty of the range of measurements is 5.6, resulting in an uncertainty of 21% from this source.

There are two approaches to determine the combined uncertainty from the above five potential sources of uncertainty. 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 + 21 = +62%. However, a more reasonable approach would be 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 various uncertainties, which is ±34.2%. Rounding this up to ±35% would seem to provide an adequate and suitably conservative indication of uncertainty. Therefore, for an individual derived organ dose, a total combined standard uncertainty of ±35% can be assumed; for further conservatism, dose reconstructors should assume that errors are all positive and use only +35%.

3.7 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 (SRDB).

Vernon E. Shockley served as one of the initial Subject Experts for this document. Mr. Shockley was previously employed at Hanford and his work involved management, direction or implementation of radiation protection and/or health physics program policies, procedures or practices related to atomic weapons activities at the site. This revision has been overseen by a Document Owner who is fully responsible for the content, including all findings and conclusions. In all cases where such information or prior studies or writings are included or relied upon by Mr. Shockley, those materials are fully attributed to the source.

Ronald L. Kathren served as one of the initial Subject Experts for this document. Mr. Kathren was previously employed at Hanford and his work involved management, direction or implementation of radiation protection and/or health physics program policies, procedures or practices related to atomic weapons activities at the site. This revision has been overseen by a Document Owner who is fully responsible for the content, including all findings and conclusions. In all cases where such information or prior studies or writings are included or relied upon by Mr. Kathren, those materials are fully attributed to the source.

Fred Duncan assumed responsibility as Document Owner for this document in September, 2008. Mr. Duncan replaced Edward Scalsky when Mr. Scalsky's employer declared a new corporate conflict of interest for the Hanford Site. Mr. Scalsky continues to participate on this document team in the appropriate role of Subject Expert in compliance with the NIOSH Conflict or Bias policy.

[1] Thomas, Elyse. ORAU Team. Principal Medical Dosimetrist. September 2009. Review of claim file records from Hanford.

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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 ($J\ kg^{-1}$) and is given the special name gray (Gy).

anterior-posterior (AP)
Physical orientation of the body relative to a penetrating directional radiation such that the radiation passes through the body from the front to the back. See *exposure geometry*.

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

entrance skin exposure
Air kerma in air without backscatter at the point of entry into the body. Also called entrance kerma in air. See *kerma*.

exposure geometry
Orientation (physical positioning) of a person or object in relation to a radiation source. This geometry is a factor in the radiation dose to various parts of the body. See *anterior-posterior*, *posterior-anterior*, and *lateral* in relation to radiography.

film speed
Measure of the sensitivity of film to X-rays or light.

filtration
Process of selective absorption of an X-ray beam, usually with millimeter thicknesses of aluminum material between the X-ray source and the film. Usually measured in millimeters of aluminum. See *beam quality* and *half-value layer*.

focal spot
Apparent size of the area of the anode of an X-ray tube bombarded by accelerated electrons when viewed from the central axis of the useful radiation beam.

gray (Gy)
International System unit of absorbed radiation dose, which is the amount of energy from any type of ionizing radiation deposited in any medium; 1 gray equals 1 joule per kilogram or 100 rads.

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

half-value layer (HVL)
Thickness of a specified substance, usually in millimeters of aluminum, that filters an X-ray beam to reduce the kerma in air rate by one-half. See *filtration*.

Interactive RadioEpidemiological Program (IREP)

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

International Commission on Radiological Protection (ICRP)

International private scientific organization established to advance the science of radiological protection in particular by providing recommendations and guidance on all aspects of protection against ionizing radiation.

inverse square law

Mathematical relationship between two quantities in which one quantity varies inversely as the square of the other (e.g., radiation exposure is four times larger at 5 feet from a source than at 10 feet).

kerma

Measure in units of absorbed dose (usually grays but sometimes rads) of the energy released by radiation from a given amount of a substance. Kerma is the sum of the initial kinetic energies of all the charged ionizing particles liberated by uncharged ionizing particles (neutrons and photons) per unit mass of a specified material. The word derives from kinetic energy released per unit mass.

kiloelectron-volt (keV)

Unit of particle energy equal to 1,000 (1×10^3) electron-volts.

lateral (LAT)

Orientation of the body during an X-ray procedure in which the X-rays pass from one side of the body to the other. See *exposure geometry*.

milliammeter

Instrument for measuring electric current in milliamperes.

National Council on Radiation Protection and Measurements (NCRP)

Private U.S. public service organization chartered by the U.S. Congress to formulate and disseminate information, guidance, and recommendations on radiation protection and measurements.

organ dose

Dose to a given organ from an X-ray procedure.

photofluorography (PFG)

Historical radiographic technique used for chest images for screening a large number of people in a short period of time. The X-ray image produced on a fluorescent screen was photographed on 4- by 5-inch film. PFG was the primary method of screening large populations for tuberculosis before the advent of nonradiographic screening methods. Also called fluorography or mass miniature radiography.

photon

Quantum of electromagnetic energy generally regarded as a discrete particle having zero rest mass, no electric charge, and an indefinitely long lifetime. The entire range of electromagnetic radiation that extends in frequency from 10^{23} cycles per second (hertz) to 0 hertz.

posterior-anterior (P/A)
Physical orientation of the body relative to a penetrating directional radiation field such that the radiation passes through the body from the back to the front. See *exposure geometry*.

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

probability of causation (POC)
For purposes of dose reconstruction for the Energy Employees Occupational Illness Compensation Act, the percent likelihood, at the 99th percentile, that a worker incurred a particular cancer from occupational exposure to radiation.

radiograph
Static images produced on radiographic film by gamma rays or X-rays after passing through matter. In the context of EEOICPA, radiographs are X-ray images of the various parts of the body used to screen for disease. See *radiology*.

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

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

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

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

technique
Combination of X-ray machine settings used to produce radiographs, which consists of the applied kilovoltage, tube current (milliamperes), and exposure time (seconds). The last two parameters are often multiplied to yield the electric charge that has crossed the X-ray tube during the exposure in units of milliampere-seconds. Any combination of time and tube current that produces a given product in milliampere-seconds produces the same exposure for a fixed peak kilovoltage. Also called technic.

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

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

variable
In a mathematical formula, a quantity or function that can assume any given value or set of values.

X-ray

(1) See *X-ray radiation*. (2) See *radiograph*.

X-ray radiation

Electromagnetic radiation (photons) produced by bombardment of atoms by accelerated particles. X-rays are produced by various mechanisms including bremsstrahlung and electron shell transitions within atoms (characteristic X-rays). Once formed, there is no difference between X-rays and gamma rays, but gamma photons originate inside the nucleus of an atom.

X-ray tube

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