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PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
04/20/2004	00	New technical basis document addressing occupational medical dose for the Oak Ridge National Laboratory. First approved issue. Initiated by Robert E. Burns, Jr.
10/29/2004	01	Revised to remove 25% timing error correction from ESE and organ dose values from PA chest exams between 1964 and 1990. Approved issue of Revision 01. Initiated by Robert E. Burns, Jr.
07/21/2006	01 PC-1	Approved page change revision initiated to incorporate recent direction from NIOSH to include details for the definition of a DOE facility on page 5 in Section 3.1. Adds Purpose and Scope sections on page 6. Revised to delete the uterus as a surrogate organ to the ovaries on page 15 in Section 3.5 and on page 24 in Table 3-7 in Section 3.4. Makes corrections in Table 3-5 on pages 20 and 21 and in Table 3-6 on pages 22 and 23 in Section 3.6. Incorporates NIOSH formal review comments. No sections were deleted. This revision results in a reduction in assigned dose and no PER is required. Initiated by Robert E. Burns, Jr. Approval: Signature on File 07/11/2006 Robert E. Burns, Jr., TBD Team Leader Signature on File 07/11/2006 John M. Byrne, Task 3 Manager Signature on File 07/11/2006 Edward F. Maher, Task 5 Manager Signature on File 07/20/2006 Kate Kimpan, Project Director Signature on File 07/21/2006 James W. Neton, Associate Director for Science
10/01/2007	02	Approved Revision 02 initiated to include Attribution and Annotation section. Incorporates formal internal review comments most of which were editorial and pertained to more than the added Attributions and Annotations section. Table 3-6 had the factor of two removed that was applied to the organ dose values for the ovaries, testes, and uterus. Incorporates formal NIOSH review comments. Training required: As determined by the Task Manager. Initiated by Robert E. Burns.

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ACRONYMS AND ABBREVIATIONS

Al	aluminum
AP	anterior-posterior
cGy	centigray
cm	centimeter
DCF	dose conversion factor
DOE	U.S. Department of Energy
EEOICPA	Energy Employees Occupational Illness Compensation Program Act of 2000
ESE	entrance skin exposure
Gy	gray
HVL	half-value layer
ICRP	International Commission on Radiological Protection
ICRU	International Commission on Radiological Units and Measurements
IREP	Interactive RadioEpidemiological Program
kVp	applied kilovoltage, kilovolts-peak
LAT	lateral
mA	milliampere
mAs	milliampere-second
mGy	milligray
mm	millimeter
mrad	millirad
NBS	National Bureau of Standards
NCRP	National Council on Radiation Protection and Measurements
NIOSH	National Institute for Occupational Safety and Health
ORAU	Oak Ridge Associated Universities
ORNL	Oak Ridge National Laboratory
ORR	Oak Ridge Reservation
PA	posterior-anterior
PFG	photofluorography
POC	probability of causation
R	roentgen
RMS	root mean square
RT	radiology technician
SID	source-to-image distance
SRDB Ref ID	Site Research Database Reference Identification (number)
SSD	source-to-skin distance

U.S.C.	United States Code
X-10	The Oak Ridge National Laboratory site
Y-12	Y-12 National Nuclear Security Complex
§	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 for 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) define "performance of duty" for DOE employees with a covered cancer or restrict the "duty" to nuclear weapons work.

As noted above, the statute 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 contains an exclusion with respect to the Naval Nuclear Propulsion Program, 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 dosimetry monitoring results are considered valid for use in 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:

- Radiation from naturally occurring radon present in conventional structures
- Radiation from diagnostic X-rays received in the treatment of work-related injuries

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

3.1.1 Purpose

Medical X-ray procedures required as preplacement, annual, and termination examinations were and are still a contributor to the occupational radiation exposure of workers at the Oak Ridge National Laboratory (ORNL) as defined under EEOICPA. Unlike occupational exposures incurred during normal work processes, individual medical X-ray exposures were not monitored, necessitating the use of the information provided in this document in the reconstruction of dose from these exposures.

3.1.2 Scope

This document describes the technical aspects of dose reconstruction from medical X-rays administered prior to employment (preplacement) and periodically thereafter (typically annual and termination) for screening purposes and as a condition of employment at ORNL. Photofluorographic (PFG) techniques were used from 1943 through October 3, 1947, to conduct preplacement chest examinations for potential ORNL workers.

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 AFFECTING X-RAY DOSE

A number of factors affect doses to workers from X-ray procedures. For a standard medical radiographic unit with a tungsten target (anode) and focal spot of 1-2 mm, these factors include

- The peak applied voltage on the X-ray tube (kVp)
- The tube current (mA)
- The time of exposure
- The distance from the X-ray source to the skin or organ of concern
- The waveform of the X-ray generator
- The thickness and type of metal used for filtration (beam hardening)
- The use of collimation or diaphragms to minimize the beam area
- The characteristics of the tube housing
- The type and speed of the film
- Film development procedures
- The use of screens or grids
- The physical size and thickness of the worker

While this list of factors looks formidable, in the absence of direct measurements of the beam itself, which might not be available, worker dose can be estimated with a reasonable degree of accuracy with knowledge of only the three basic machine parameters (peak applied voltage, tube current, and time of exposure) and assumptions about filtration, collimation, and waveform characteristics as necessary. The implications of these factors to worker dose are discussed below.

3.2.1 Peak Applied Voltage and Filtration

The energy of the X-ray beam, sometimes referred to as *beam quality*, is determined by the peak applied voltage (kVp) and the filtration. X-rays produced in a typical medical X-ray tube are *bremsstrahlung* radiation (a continuous distribution or spectrum of energies ranging from zero up to the voltage applied to the tube). This refers to the electronic potential that exists between the anode and cathode of the tube. For a typical unfiltered X-ray spectrum, the average photon energy is about one-third of the peak energy, or applied voltage. Hence, most X-rays produced by a given voltage are

much lower in energy than the applied voltage of the beam, and are attenuated by the filtration that exists in the tube (inherent filtration), any additional filtration used to harden the beam, and the torso or other portions of the body through which the primary X-ray beam is focused. These X-rays never reach the film and are of little value in radiography, but can contribute significantly to worker dose. To reduce the worker dose, filtration in the form of a specified thickness of absorbing material (typically aluminum) is placed in the beam after it exits the port. This absorbs a large fraction of the lower-energy X-rays that are of little or no value in making the radiograph while allowing most of the more energetic and radiographically useful X-ray photons to pass. In this manner, worker dose is reduced significantly and radiographic quality can even be enhanced. A filtered X-ray spectrum has a correspondingly higher average energy than it had before it was filtered, although the photon fluence rate entering the target area is much reduced. Such a beam is said to have been *hardened*. A corollary to this filtration technique is to use a higher applied voltage and to filter the beam relatively heavily to prevent most of the low-energy, radiographically useless photons from reaching the worker.

Beam energy is specified in terms of quality, or hardness, which in turn can be stated in terms of the half value layer (HVL) in aluminum or other metals such as copper or tin. Unfortunately, this parameter is seldom available. Even if it is known, it is of limited value, in part because it does not specify the maximum energy of the beam. In addition, it might not reflect the true beam quality, as the HVL measurement might be biased depending on how it was performed (i.e., if mathematical unfolding techniques were not applied to correct for the effect of the absorbers used in the measurement). What is commonly, although not always, available is the kVp of the machine and the external filtration that might be added for hardening the beam. All X-ray tubes have so-called inherent filtration, which includes glass in the walls, oil that surrounds the tube for cooling, and the window or port of the tube head. This window, the thinnest part of the tube housing in medical radiographic units, is typically equivalent to 0.5 mm Al in attenuation and, hence, provides little beam hardening. The inherent filtration asserted by the ORNL medical department staff for the original X-ray machine installed in October 1947 (Picker Model R-2) was 0.04 mm Al. Given the disparity between this value and what is typical, a beam quality with an HVL of 1.5 mm Al was assumed for the assessment of worker exposures from this unit [1]. The total filtration given for this device was found to be documented (Lincoln and Gupton 1957, 1958) as 1 mm Al and was used to estimate the entrance skin exposure[2] (ESE) values for lumbar spine X-ray examinations for the machine used between 1947 and 1963. The documented skin dose in these same reports was low (21 mrad) for the PA chest X-ray examination as compared to skin dose from other chest X-rays given during that timeframe. The skin exposure for that timeframe was estimated using operating parameters [2].

Although the benefits of filtration with respect to improved radiographic images were known and understood very early on, radiographs were initially made with no added filtration. Recommendations made in 1937 by the International Committee for Radiological Units and Measurements (ICRU), albeit not specific for thickness, specified aluminum filters for X-rays of 20 to 120 kVp, which incorporated the diagnostic X-ray energy range available at that time (ICRU 1937). Typical external filtration in the 1940s ranged from none to 1 mm Al. This was in line with 1936 recommendations of the U.S. Advisory Committee on X-Ray and Radium Protection, which later became the National Council on Radiation Protection and Measurements (NCRP), which called for 0.5 mm of Al equivalent for radiographic installations, and 1 mm Al for fluoroscopy (NBS 1936). In 1949, the NCRP recommended 1-mm Al filtration for radiography of thick parts of the body such as the chest (NBS1949); this thickness was used during World War II in 100-mA units in larger military hospitals. Recommended thicknesses were later increased; in 1955, the NCRP recommendation for diagnostic

[2] Throughout this document, *italics* are used to differentiate *exposure* in the special sense from exposure in the general sense. Thus *exposure* refers to *exposure in the special sense*. Many publications, including NCRP (1985) and ICRU (1998), discuss exposure in both the general and special sense. The definition and application of the quantity exposure and its concomitant unit the roentgen have undergone important modifications over the years, as documented in the literature.

X-ray units called for 2-mm total Al filtration for new machines (NBS 1955). This increased in 1968 to 2.5 mm for medical diagnostic units operating above 70 kVp (NCRP 1968). For machines already in operation, these recommended filter thicknesses might not have been used for some time after the date of the recommendation.

The relationship of beam intensity[3] to applied voltage and filtration is complex and to some extent machine-specific and, therefore, is best determined empirically. In the absence of empirical data for a specific machine, however, there are adequate contemporary empirical and theoretical data on which to determine machine output within a reasonable degree of uncertainty. Additional filtration reduces the ESE, generally in an exponential manner. For a typical single-phase, half-, full-, or self-rectified machine operating in the diagnostic range of 80 to 100 kVp, each additional millimeter of Al filtration will effect a reduction of about 40% in the ESE (Trout, Kelley, and Cathey 1952; Taylor 1957). Thus, the approximate intensity reduction afforded by any thickness of Al filtration can be determined by the following exponential equation:

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

or

$$\ln (I/I_o) = -0.4t \quad (3\text{-}1)$$

where t is the thickness of Al in millimeters, and I and I_o are the beam intensities with and without the filter, respectively. In the absence of specific measurements or empirical data, this correction, which is consistent with the guidance in *External Dose Reconstruction Implementation Guideline* (NIOSH 2006), can be applied to determine the effect of filtration on beam intensity.

Similarly, increasing the kVp will increase the beam intensity or exposure rate. This can be calculated using Kramer's rule, but such calculations are difficult, complex, and time-consuming, even with high-speed computers, and are at best approximations. However, many empirical studies of beam intensity as a function of kVp provide ample credible evidence to show that, for a given amount of filtration, increasing the applied kVp will increase the beam intensity according to the 1.7 power of the applied kilovoltage (Handloser and Love 1951; Trout, Kelley, and Cathey 1952; Kathren 1965; BRH 1970). In the absence of specific measurements or empirical data, this function, which is consistent with the guidance in NIOSH (2006), can be applied to determine the effect of applied voltage on beam intensity.

3.2.2 Current and Exposure Time

X-ray exposures are typically specified in terms of milliampere-seconds (mAs), the product of X-ray tube current and exposure time. Thus, all factors being equal (e.g., kVp, filtration, film speed, development, and screen combination), radiation exposure is directly proportional to the product of the tube current and exposure time, mAs. The current in an X-ray tube refers to the number of electrons accelerated across the evacuated volume of the tube, flowing from the cathode to the anode. For a given applied voltage, the number of X-ray photons produced, and therefore the exposure, will, at least in theory, be directly proportional to the X-ray tube current. This is and has been true for most medical radiography units over their design tube current range. Thus, in the absence of measurements or other data or information to the contrary, it is reasonable and consistent with long-standing radiographic practice (Sante 1946) to assume linearity of exposure with tube current for a given kVp and filtration.

[3] As used herein, *beam intensity* refers to the output of the machine in terms of exposure in the special sense per mAs. Exposure in the special sense is referenced to ionization in air and, as such, is not a dose quantity.

Exposure time refers to the period the beam was on or the machine was producing X-rays and is, for all practical purposes, linear with exposure. To avoid or minimize image blurring from the beating heart, exposure time for chest radiography was minimized, and the current proportionally increased to obtain the desired exposure in terms of mAs. However, earlier medical radiographic units had mechanical timers with accuracies that were not as good as those of the electronic timers used on later units. It was noted in two surveys conducted at ORNL (Ohnesorge 1979 and Halliburton 1985) that the timer for the Westinghouse Riviera instrument was incorrect by between 20 to 25%. Gross systematic errors in timer accuracy, however, are typically unlikely in most units because they would result in over- or underexposure of the radiograph and, therefore, would be quickly detected and corrected. Small random errors, which might produce uncertainties of perhaps ±20% in the exposure, are more subtle.

Photofluorography of the chest, which resulted in much greater worker doses than a standard radiographic procedure, appears to have been used by Oak Ridge Hospital from the inception of activities at ORNL (ca. early 1943) until the ORNL Medical Department began using its own conventional radiographic X-ray machine in early October 1947. It was stated by the Radiology Technician who began working at ORNL in September 1947 that no PFG exams of the chest were performed at the ORNL site during physical examinations and none were observed during the site visit (Tuck 2003). Although PFG examinations were used as an inexpensive method of conducting tuberculosis screenings for large populations, they caused much higher exposures than conventional radiographic chest X-ray examinations due to the need for increased exposure time to fluoresce the image screen. It appears that stereoscopic PFG views (with 2 exposures) using smaller film (4 × 10 in.) were used to conduct preplacement examinations for all ORNL workers from 1943 through September 1947 [3]. It also appears that if the initial examination indicated the need for a follow-up, these were performed via a conventional posterior-anterior (PA) view onto 14- × 17-in. film [4]. (A fluoroscopy X-ray unit was acquired at some time early in the history of the ORNL site, but was used for a short period of time and only for conducting upper gastrointestinal examinations.)

3.2.3 Distance

X-ray beam intensity is a function of distance from the target, approximating the inverse square at large distances from the tube. Radiographic chest films were taken at a standard source-to-image distance (SID)[4] of 72 in. (*source* refers to the focal spot of the tube and *image* to the plane of the film). Lumbar spine projections were performed at a SID of 39 in. (see Table 3-3). The distance to the worker who was between the source and the film cassette, which is sometimes expressed in terms of the source-to-skin distance (SSD), was somewhat smaller and, therefore, the ESE to the worker was somewhat greater than the exposure at the plane of the film. PA Chest and Anterior Posterior (AP) Lumbar spine thicknesses were assumed to be 26 cm while the thickness of the Lateral Chest and Lateral Lumbar Spine was 34 cm. It further was assumed that a distance of 5 cm existed between the film and the closest surface of the body to the film. These measurements are reasonable and were used to estimate the ESEs for the various X-ray examinations for ORNL employees) [5].

3.2.4 Waveform and Collimation Characteristics

Among other factors that could affect worker dose are waveform and collimation. X-ray waveforms are of four types: half-wave rectified, which were present in the earliest X-ray equipment; full-wave rectified; constant potential (as defined in NCRP Report 33); and high-frequency generators. A half-wave rectified machine produces 60 half-sinusoidal shaped pulses of X-rays per second, each with duration of 1/120 of a second. A full-wave rectified machine produces 120 half-sinusoidal pulses per

[4] Also known as film-to-focus distance (FFD).

second, each with duration of 1/120 second. Thus, for a given setting of kVp and mA, the intensity of the beam from a half-wave rectified machine is half that of the beam from the full-wave rectified type. Constant potential machines, as defined in NCRP Report 33, and high-frequency generators produce a more or less steady (i.e., unpulsed) output of X-rays and have somewhat greater beam intensity – approximately 10% more – than full-wave rectified machines operating at the same kVp and mA. (It was assumed that single phase units were used until 1990 when a high-frequency generator unit was procured for ORNL.) [6]

Collimation refers to the size of beam. The early philosophy was to use a fairly large aperture with limited collimation to ensure that the entire area of interest was included in the radiograph. Later, because of radiation exposure concerns, beams were collimated such that the smallest beam consistent with the area of interest was used, thereby limiting the area of the worker exposed and, in the case of chest radiography, minimizing dose to organs such as gonads, thyroid, and gastrointestinal tract. A practical check of collimation can be made by reference to the radiograph; a well-collimated beam will leave a small unexposed area at the edges of the radiograph, while a poorly collimated beam will produce a radiograph that is exposed over all of its area. Discussions with the radiology technician who worked at ORNL from 1947 until recently indicated that the X-ray beams used at ORNL were well-collimated (Tuck 2003) and a paper (Lincoln and Gupton 1958) indicates that a 20 cm cone was used in the mid-1950s at ORNL to reduce secondary photons and therefore collimated the primary beam. Nonetheless, results given in a table (Lincoln and Gupton 1958) indicate that the dose conversion factors (DCFs) given in ICRP 34 for a well-collimated beam may not apply. Therefore DCFs for poorly collimated beams found in ORAUT-OTIB-0006, Table 4.0-1 (ORAUT 2005), were used until a newer X-ray unit was procured in 1963. Another document from the same author (Lincoln and Gupton 1957) stated that "Gonad doses determined from these phantom measurements are probably exaggerated, as the phantom is somewhat smaller than the average adult."

3.2.5 Screens, Grids, and Other Factors Potentially Affecting Worker Dose

A number of other factors affect the X-ray exposure required to obtain a proper radiograph and, therefore, 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 characteristics of applied voltage, time, and current are known along with the amount of primary beam filtration. For completeness, this document mentions these factors, which are tube housing, type and speed of film, development procedure, screens, and grids.

X-ray tubes used for medical radiography are typically enclosed in protective lead tube housings and the primary beam is emitted through a port or window in the side of the housing. Although some reduction of worker dose is achieved, largely through elimination of scattered radiation and improved collimation, the primary purpose of the diagnostic tube housing is the protection of the operator, unexposed X-ray film, and nearby individuals other than the worker. This issue is moot, however, because virtually all X-ray tubes, and certainly those used at ORNL since its inception, had protective tube housings.

The amount of exposure needed for a suitable radiograph is in some measure a function of film speed and development. Fine-grain emulsions produce a superior radiographic image but require additional exposure in comparison to fast films. In addition, underdevelopment of films requires additional exposure to achieve satisfactory radiographic quality. Intensifying screens are used in the cassette to augment the radiographic effect and thereby increase film speed and reduce worker dose. Grids, specifically the Potter-Bucky diaphragm (colloquially known as a Bucky), are sometimes utilized for thick-section radiography, but rarely for chest radiography except with large workers. In any case, the

above (i.e., kVp, mA, exposure time, and filtration) are all factored into the technique used and, except in rare instances and a virtually complete absence of other data, are not important in dose reconstruction.

3.3 X-RAY DOSES TO ORNL WORKERS, 1943 TO PRESENT

The effects of various technical factors and how they affect X-ray beam intensity are summarized in Table 3-1.

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

Parameter	Units	Relationship with intensity
Applied voltage	kVp	Intensity proportional to 1.7 power of kVp
Tube current	mA	Linear
Exposure time	s	Linear
Filtration	mm Al	Intensity decreases by ~40% for each additional mm Al
Distance	d	Approximately inverse square relations ($1/d^2$)
Uncertainty	±30 %	Assume all errors are positive, +30% should be used

The current ORNL Medical Department provided a description of radiographic procedures that have been used to conduct X-ray examinations for workers at the ORNL site (ORNL 2002, see Table 3-2). Before October 3, 1947, all radiology examinations were performed at Oak Ridge Hospital in Oak Ridge, Tennessee. A review of several individual records in the ORNL Medical Records vault seems to confirm that many early preplacement medical examinations were conducted at Oak Ridge Hospital from 1943 through 1947. The vault contains 4- × 10-in., stereoscopic PFG images; a sampling of ~15% of these images indicated beginning and end dates of March 1944 and September 1945, respectively, for the examinations. The ESE and organ dose values in Tables 3-4 and 3-6, respectively, for PFG examinations are based on the assumption that stereo imaging was always employed for such examinations; that is, each procedure consisted of two exposures for each individual [7]. If it is determined that a PFG conducted for a given individual consisted of only one 4- × 5-in. view, the values in these tables should be divided by 2. Although 14- × 17-in. radiographic PA chest images were in individual medical X-ray files from 1943 through 1947, the use of stereo PFG for preplacement examinations during that period cannot be discounted. Such examinations should be assumed, therefore, for each individual who began employment during that period unless there is evidence to the contrary [8]. Almost exclusively, individual medical files noted that retake, routine annual, and termination X-ray films taken from 1943 through 1947 were 14- × 17-in. radiographic PA chest images. [However, during the review of radiographic images archived by the ORNL medical

Table 3-2. X-ray operating parameters, dates of use, and frequency of examinations (provided by ORNL).

Dates	X-ray equipment	Location	Exam/Projections	Techniques	People involved	Age dependence
Prior to October 3, 1947	Not accurately known, but possibly a Westinghouse Fluorodex 60-120 kVp	Oak Ridge Hospital	Stereo PFG (2 views) for preplacement exams PA chest X-ray for other exams	Not accurately known	Employees and preplacement	
October 3, 1947 to end of 1963	Picker 200-mA Control & Generator- Model R-2	ORNL	Chest X-ray, one film, PA projection	Filter=0.04 mm Al 76 kVp, 200 mA @ 1/20 sec., 183 cm. distance, w/ 20-cm cone	Employees and Preplacement	
April 6, 1950, to September 23, 1953	Picker 200-mA Control & Generator- Model R-2	ORNL	Lumbar spine series, 4 films: AP, AP spot, Lateral, and Lateral spot	AP & AP spot Filter=0.04 mm Al, 80 kVp, 40 mA, 4 sec @ 99 cm. distance, w/ 20-cm cone	Craft workers	
				LAT & LAT spot Filter=0.04 mm Al, 86 kVp, 40 mA, 8 sec @ 99 cm distance, w/ 20-cm cone		
End of 1963 to 1976	Westinghouse Riviera 300 mA, 125 kVp	ORNL	Chest X-ray, one film, PA projection	Filter 1.5 mm Al, 107 kVp, 300 mA, 0.01 sec, @ 183 cm distance	Preplacement	
1976 to November 1990	Westinghouse Riviera 300 mA, 125 kVp	ORNL	Chest X-ray, one film, PA projection	Filter 1.5 mm Al, 107 kVp, 300 mA, 0.01 sec, @ 183 cm distance	Preplacement; employees in respirator/asbestos programs (every 3 years)	
November 1990 to April 18, 1996	Bennett High Frequency Quartz 600 Series	ORNL	Chest X-ray, one film, PA projection	Filter 2.0 mm Al, 110 kVp, 300 mA, 3.2 mAs, @ 183 cm distance	Preplacement; respirator/asbestos program employees	<40 years old, every 3 years; 40-49 years old, every 2 years; >49 years old, every year
April 18, 1996 to 2002	Bennett High Frequency Quartz 600 Series	ORNL	Chest X-ray, two films, PA and lateral projections	PA Filter 2.0 mm Al, 110 kVp, 300 mA, 3.2 mAs, @ 183 cm distance	Preplacement; respirator/asbestos program employees	<40 years old, every 3 years; 40-49 years old, every 2 years; >49 years old, every year
				Lateral Filter 2.0 mm Al, 125 kVp, 300 mA, 8.0 mAs, @ 183 cm distance		
2002	Bennett High Frequency Quartz 600 Series	ORNL	Chest X-ray, two films, PA and lateral projections	PA Filter 2.0 mm Al, 110 kVp, 300 mA, 3.2 mAs, @ 183 cm distance	Asbestos program employees	Annually for workers 45 and over
				Lateral Filter 2.0 mm Al, 125 kVp, 300 mA, 8.0 mAs, @ 183 cm distance		

department, two stereo PFG films that were taken approximately 1 year apart were located for an individual. The initial PFG was followed approximately 2 weeks later with a 14- × 17-in. radiographic PA chest image due to problems in viewing the initial film. The medical record indicated that an annual chest X-ray was taken approximately 1 year after the initial PFG. This annual chest X-ray was a PFG examination.]

The use of PFG imaging was common during that period because it was less expensive than the conventional (e.g., larger) X-ray films and could quickly be used as a means of screening large numbers of individuals for tuberculosis, which was a public health concern at the time. Follow-up examinations with conventional-sized films (e.g., 14- × 17-in.) were taken as needed to either confirm original results or to get clearer images.

There is an indication from documentation at Y-12 that some medical examinations were performed in Knoxville, Tennessee, but it is not known at what frequency these were performed or if medical X-rays for employment purposes for ORNL workers were ever taken in Knoxville. All X-ray films reviewed in the ORNL Medical Records vault were inscribed either "OR Hospital" or "Oak Ridge National Lab." Nonetheless, the assumption of a 0.2-R exposure for a PA chest radiograph (ORAUT 2005) at a Knoxville hospital would be favorable to claimants, and the absorbed dose values in Table 3-6 can be used to estimate organ doses for other hospitals in the 1940s that might have performed PA chest X-ray examinations [9]. (The United States Army Center for Health Protection and Preventative Medicine was contacted, but no historic information regarding type of equipment used, procedures, or equipment operating parameters was obtained nor was information that Oak Ridge Hospital even existed as an Army hospital.) Oak Ridge Hospital became Methodist Hospital of Oak Ridge in 1959. Historical records transferred from Oak Ridge Hospital to ORNL appear to have either been incorporated in individual medical files or remain in the X-ray pouches. Based on the gaps in time for the PFGs noted above, it is not clear if all medical and X-ray records were transferred from Oak Ridge Hospital to ORNL Medical. It is possible that records were sent to the Oak Ridge Reservation (ORR) site at which the employee was active at the time and were not transferred with them when they transferred to other ORR sites.

Information provided by the ORNL medical department indicated that from October 3, 1947, to the present, all medical X-rays for screening conducted in the ORNL Medical area used conventional, radiographic (non-PFG) equipment. A fluoroscopic unit was used at ORNL at one point for conducting upper gastrointestinal (GI) series examinations, but was never used for examinations that would be considered occupational exposure under EEOICPA.

After ORNL stopped performing upper GI examinations (believed to be in the early 1950s), and at the request of K. Z. Morgan (director of ORNL's health physics department), the radiology technician (RT) constructed a shield from the rubberized-lead, fluoroscopy apron that male workers could use to shield their gonads during routine employment screenings (Tuck 2003). (The RT added that K. Z. Morgan was adamant about radiation protection in medical procedures.) The RT stated that workers would hold the shield at approximately waist level for a PA chest exam or place it across their thighs for AP (or similar) exposures. It was the RT's assertion that only male workers would use the shield, as it would interfere with the region of interest if females used it to shield the ovaries. The RT would check the shield for leaks by exposing an X-ray cassette with the shield in front of it. Use of the shield was discontinued (the RT could not recall when) in favor of better collimation of the X-ray beam.

Table 3-2 lists radiographic examinations that would be considered occupational medical exposures as defined under EEOICPA for workers at ORNL after October 3, 1947, identifying the equipment and operating parameters used during the different periods. Two items in the description provided by the ORNL Medical Department that appear to be inconsistent for equipment in use at the time are the

inherent (and total) filtration of the initial Picker unit and the exposure time used with the Westinghouse Riviera unit. Typical inherent filtration for an X-ray tube at the time was approximately 0.5 mm Al (TM 1944), with additional filtration added to harden the beam. The reported exposure time of 0.01 second with a tube current of 300 mA gives a 3-mAs intensity, which is believed to be low for chest X-rays. Rather than using the given 0.01-sec exposure time, it is assumed that the exposure time was 0.1 second, making exposures for PA chest films 30 mAs when using the Picker X-ray unit. The radiographic examinations performed at ORNL are listed below:

- Chest: PA and lateral
- Lumbar spine series: AP, AP Spot, lateral, and lateral spot

Accordingly, only doses from these exams, in addition to the PFG exams conducted at the Oak Ridge Hospital from 1943 to 1947, were evaluated to support dose reconstructions at the ORNL site. Table 3-2 lists the three radiographic machines that have been used at ORNL and the applied voltage, tube current, exposure time, and SID used for examinations. Medical records for individuals who worked at ORNL in the early years indicated that radiographic chest examinations made during the preplacement, routine annual, and termination physicals were the norm until the 1970s, when individuals were able to waive annual chest X-ray examinations. [Information in the individual's medical files and X-ray log books available in the ORNL Medical Records vault should enable a dose reconstructor to estimate the number of occupational medical X-ray examinations from October 3, 1947 for a given individual. Information for workers who worked at the site from 1943 to October 3, 1947, was present in many of the medical files that were reviewed. This information may be provided by the ORNL Medical staff for use by the dose reconstructor to determine number of examinations.]

The lumbar spine series of examinations was reserved for preplacement X-ray examinations for craft employees (pipefitters, carpenters, etc.) to determine if they had pre-existing back problems prior to hiring. The information provided by the ORNL medical department indicated that the Lumbar Spine series of examinations, which took place from April 6, 1950, to September 23, 1953, would have been conducted along with a PA chest examination. Although the spot X-ray examinations would have used conic or cylindrical shields to reduce the size of the field and, therefore, would have significantly reduced exposures to organs outside the field of view, the ESEs within the field would have been unlikely to change. For dose reconstruction purposes, it is assumed that two AP and two lateral lumbar spine examinations would have been conducted on preplacement individuals during this period and this is favorable to claimants.

A review of the claim files from ORNL indicates that records often state that standard chest X-rays were taken in the AP direction. This is believed to be an error, as chest X-rays are almost always done (at least on ambulatory workers) PA. The assumption for this project, therefore, is that chest X-rays were performed PA, and not AP like some of the records state.

Field surveys performed at the Oak Ridge Hospital in 1956 indicated that the skin exposure for a single exposure PA Chest PFG was 1.4 R (Gupton, Tuck and Lincoln 1956). This value was doubled to 2.8 R to account for a stereo (two exposure) procedure. The 2.8 R ESE value was used for the calculation of organ dose from PFG examinations used in preplacement screenings performed prior to October 3, 1947. Organ dose values provided for PFG exams should be divided by 2 if it is known that only a single PFG exposure was made. For retake, annual, or termination chest X-ray exams users should assume that standard 14- × 17-in. PA films were made unless otherwise noted in the medical records. Organ doses have been provided in Table 3-6 for both stereo PFG exams and standard PA chest exams for the period prior to October 3, 1947.

A potential problem common to all X-ray examination procedures relates to the conversion of exposure represented by ESE to absorbed organ dose, and to changes in the definition of dose and other dose quantities. Over the 50 or so years since the beginning of ORNL operations, the quantity known today as *exposure* has undergone several important conceptual changes, as has the application of the unit of exposure, the roentgen (R), which in itself is obsolete. Thus, there is much confusion about the definition of *exposure* and its associated unit. At one time, the Roentgen was used to quantify the dose from electromagnetic radiation in air and, when this proved confusing and inexact, was defined as *exposure dose* to distinguish it from the term *absorbed dose*, which was applicable to any type of radiation.

Additional confusion was engendered by changes in the values of the conversion coefficients used to convert exposure to absorbed dose. At various times an exposure of 1 R was equated to a soft tissue dose of 0.83, 0.877, or 0.93 rad. Thus, an exposure to air of 1 R would result in an absorbed dose of somewhat less than 1 rad (= 1 cGy = 10 mGy). However, it was customary in radiation protection practice and regulation to use the units R and rad interchangeably. This resulted in an inherent overestimate of reported dose or dose equivalent since dosimeters were typically calibrated against a field measured in R. Further complicating the conversion of ESE in terms of exposure to absorbed dose is the contemporary trend to refer to X-ray intensity in terms of the quantity *kerma*, which is measured in the same units as absorbed dose. Typically, the numerical value of kerma is slightly lower than the corresponding value of absorbed dose. Thus, to avoid any risk of dose underestimation, 1 R of exposure was taken to be equal to1 rad of absorbed dose and to 1 rad (10 mGy) of kerma.

The ESE values for each X-ray generating device and radiographic examinations used at ORNL are listed in Table 3-4. If site-specific measured ESE data were not obtained from the literature, ESEs were estimated based on knowledge of the operating parameters of the X-ray tube, assumed worker thickness, assumed distance between worker and film, and technique used. Both Lincoln and Gupton documents (1957, 1958) provided measured ESE values for lumbar spine examinations conducted in the mid-1950s. These values were used to estimate organ doses given in Table 3-6 over the applicable time period. In addition, measured exposures to the testes, ovaries, and skin were used from this document when available. Identification and operating parameters for X-ray equipment at Oak Ridge Hospital in use from 1943 through October 3, 1947 were not located. However, a 1956 survey of the Hospital's PFG unit indicated an exposure to the skin of 1.4 R (Gupton, Tuck and Lincoln 1956). This value was doubled to 2.8 R to account for two PFG exposures, i.e. a stereo procedure. An ESE value of 0.2 R (ORAUT 2005) was used to calculate organ dose values for radiographic PA chest examinations performed at Oak Ridge Hospital or elsewhere during this period (i.e., prior to October, 1947) [10].

Conversions from ESEs to organ doses were done using DCFs from Tables A2 through A9 of ICRP Publication 34, "Protection of the Patient in Diagnostic Radiology" (ICRP 1982), where the photon beams were well-collimated. However, early X-ray units typically did not provide adequate collimation to reduce organ exposures outside the primary beam. Thus, for chest X-ray procedures performed prior to 1963, DCF values from Table 4.0-1 of ORAUT-OTIB-0006 (ORAUT 2005) were used to estimate organ doses. [Where DCF values were not provided in Table 4.0-1 (i.e., for HVLs equivalent to 1.5 and 2.5 mm of Al), guidance was provided by the Oak Ridge Associated Universities (ORAU) Team Medical X-ray Lead to estimate and verify the values used in Table 3-5 of this report.] The DCF tables from ICRP Publication 34 provide average absorbed organ doses for specific selected medical radiography procedures related to an entrance air kerma without backscatter of 1 Gy for various beam qualities expressed in terms of HVL of aluminum. However, the tables do not include all organs identified in the Interactive RadioEpidemiological Program (IREP) code. For organs included in IREP that are not specifically identified in ICRP 34, the DCFs selected were those for organs identified in

ICRP 34 that were anatomically the closest, as specified in (ORAUT 2005). Thus, the factor for lung is used for other organs in the thoracic cavity (i.e., the thymus, esophagus, stomach, and liver/gall bladder). Because an appreciable fraction of the skeleton, in particular the trabecular bone, which has a large surface-to-volume ratio, is in the trunk, the DCF for lung is used to compute dose to the bone surfaces. For organs in the abdomen (i.e., urinary bladder and colon/rectum) the DCF for the ovaries is used. These surrogate organs are summarized in Table 3-7. Because, as discussed above, 1 R was taken to be 10 mGy (1 cGy) of kerma, conversion could easily be made if the beam quality was known. Measured beam quality data were not consistently found for the ORNL site and, therefore, data that were located were not used. The applied voltage and filtration were provided in the site description (and modified as noted in Table 3-3), and an estimate of beam quality was made from these data. Because absorbed organ dose increases as a function of HVL for a given amount of filtration and exposure (mAs), the upper limit on the likely beam quality was calculated and rounded up to match the closest value in the tables in ICRP 34 or ORAUT (2005).

The assumed operating parameters used to calculate ESE and organ dose are listed in column 2 of Table 3-3. Several items were either not obtained or not clear and assumptions were necessary to be able to calculate organ doses. The examination type, frequency, ESEs, and HVLs used to calculate organ doses are listed in Table 3-4. The DCFs from ICRP 34 (1982) and ORAUT (2005) used to calculate organ doses are listed in Table 3-5. The calculated organ doses are listed in Table 3-6. ICRP 34 does not give DCFs for several organs that are inputs to IREP, so other organs were used as surrogates based on their positions in the body. The surrogates and associated organs are listed in Table 3-7. Table A6 in ICRP 34 states that DCFs were "Not computed but small compared with projections listed above" referring to dose to female breasts from lumbar spine exams. Therefore, the DCFs for the female breast from the Upper GI projections were used to estimate organ dose to the female breast from the lumbar spine projections, which should be favorable to claimants given the statement in ICRP 34.

Table 3-3. Assumptions made to operating parameters provided by ORNL and where default parameters were used.

ORNL-provided operating parameter	Assumed operating parameter
PFGs were taken at Oak Ridge Hospital for a period prior to 1947.	All employees were assumed to have received preplacement stereo PFG for employment purposes between 1943 and October 3, 1947.
Skin exposure for the Oak Ridge Hospital was given in a survey conducted by ORNL Medical Staff of PFG unit of 1.4 R.	ESE from stereo PFG = 2.8 rem (assume 2 exposure views) from the Oak Ridge Hospital survey forms.
14" × 17" radiographs of chest were noted for most site personnel for all retakes, routine annual, and termination examinations unless waived.	All retakes, routine annual, and termination examinations had PA chest X-ray examination unless medical records indicate differently.
ESE from early 14" × 17" radiographs conducted at Oak Ridge Hospital not known.	ESE for 14" × 17" radiographs not performed at ORNL = 0.2 rem (default)
Inherent filtration on Picker R-2 Unit = 0.04 mm Al.	Review of Lincoln and Gupton (1957, 1958) indicates that a filtration value of 1 mm Al was used with the Picker R-2 unit.
Total filtration for Picker R-2 unit not given.	HVL = 1.5 mm Al for organ dose calculations.
Operating parameters for Picker were 76 kVp/10 mAs (PA chest), 80 kVp/160 mAs (AP lumbar spine), and 86 kVp/320 (LAT lumbar spine).	Operating parameters for Picker are 76 kVp/10 mAs (PA chest), 80 kVp/160 mAs (AP lumbar spine), and 86 kVp/320 (LAT lumbar spine).
SIDs for all chest, PFG chest, and lumbar spine examinations were 72, 48, and 39 in., respectively.	SIDs for all chest, PFG chest, and lumbar spine examinations were 183, 122, and 99 cm, respectively.
Lumbar spine exams conducted on craft individuals from 4/6/50 to 9/23/53.	Lumbar spine exams conducted on craft individuals from 4/6/50 to 9/23/53.

ORNL-provided operating parameter	Assumed operating parameter
PA and LAT chest thicknesses and distance from body to imaging surface not given.	Assume PA and LAT chest thicknesses of 26 and 34 cm, respectively; AP and LAT LS thicknesses of 26 and 34 cm, respectively; and distance from body to imaging surface of 5 cm.
Exposure time for Westinghouse Riviera was given as 0.01 sec.	Review of equipment in use indicates that 3 mAs probably would have been low for that period and, therefore, exposure time was assumed to be 0.1 sec giving 30 mAs.
Operating parameters for Westinghouse Riviera were 107 kVp/3 mAs (PA chest).	Operating parameters for Westinghouse Riviera were 107 kVp/30 mAs (PA chest).
Operating parameters for Bennett are 110 kVp/3.2 mAs (PA chest) and 125 kVp/8 mAs (LAT chest).	Operating parameters for Bennett are 110 kVp/3.2 mAs (PA chest) and 125 kVp/8 mAs (LAT chest).
Filtration values were given of 3.0, 0.04, 1.5, and 2.0 mm Al, respectively for Oak Ridge Hospital, Picker, Westinghouse, and Bennett units. HVL values were not given by ORNL.	Assume that HVL values for Oak Ridge Hospital, Picker, Westinghouse, and Bennett units are 2.5, 1.5 (2.0 for Lumbar Spine exams), 3.0, and 3.5 mm Al, respectively.
Though cone in place, measurements of organ doses indicate that the collimation of X-ray beam was bad for the Oak Ridge Hospital and Picker units.	Use DCFs for poorly collimated beams for organ dose estimates for the Oak Ridge Hospital and Picker units. Collimation of the beam for the Westinghouse and Bennett units is assumed to be good and ICRP 34 standard DCFs used.
Waveform information not given for any unit.	Picker R-2 and Westinghouse Riviera were single-phase units; Bennett unit was high-frequency.
Preplacement examinations indicated.	Preplacement, retakes, routine annual, and termination X-ray examinations given.
Respirator and asbestos workers had different X-ray examination frequencies from approximately 1976 to present.	Assumed frequencies for respirator and asbestos workers listed in Table 3-2.

Table 3-4. Values used to calculate organ dose.

Years included	Examination	Workers affected	ESE (rem)	HVL (mm Al)
Before 1947	Stereo PFG[a]	Preplacement	2.8E+00	2.5
Before 1947	Chest PA	PFG retake, annual, and termination	2.0E-01	2.5
1947–1963	Chest PA	Preplacement, annual, and termination	5.6E-02[b]	1.5
1950–1953	LS AP[c]	Preplacement for craft workers	4.0E+00	2.0
1950–1953	LS LAT[d]	Preplacement for craft workers	1.0E+01	2.0
1964–1990	Chest PA	Preplacement, others as needed[e]	1.3E-01	3.0
1990–2002	Chest PA	Preplacement, others as needed[e]	2.2E-02	3.5
1996–2002	Chest LAT	Preplacement, others as needed[e]	6.2E-02	3.5

a. The ESE for the Stereo PFG represents both exposures. Values in Table 3-6 also indicate organ doses from both exposures.
b. Though Lincoln and Gupton (1958) indicate a measured ESE of 2.1E-02 rem, this value is low compared to expected exposures between 1947 and 1963. The ESE provided in this Table was estimated using the equipment's operating parameters. This value is approximately a factor of 2.7 greater than that measured and is favorable to claimants.
c. The ESE for the LS AP represents both the AP and spot AP exposures (i.e., 2 exposures). Values in Table 3-6 also indicate organ doses from both exposures.
d. The ESE for the LS LAT represents both the LAT and spot LAT exposures (i.e., 2 exposures). Values in Table 3-6 also indicate organ doses from both exposures.
e. Asbestos workers and others involved in respiratory protection programs examined periodically (see Table 3-2).

3.4 UNCERTAINTY ANALYSIS FOR ORNL RADIOGRAPHY DOSES

Occupational medical X-ray exposures (e.g., ESEs) at ORNL were derived from measured values and/or equipment operating factors. Several factors can introduce uncertainties or affect the X-ray machine output intensity and dose to the worker. These include:

1. Variation in applied voltage

2. Variation in tube current
3. Variation in exposure time
4. Distance from the worker to the source of the X-rays (SSD)

Table 3-5. DCFs (average absorbed dose per unit entrance air kerma) for selected X-ray projections, organs, and beam qualities.[a]

Organ	View [b]	Source-image distance (cm)	Image receptor size (cm)	Dose conversion factor (mGy per Gy air kerma) for HVL = 1.5 mm Al	Dose conversion factor (mGy per Gy air kerma) for HVL = 2.0 mm Al	Dose conversion factor (mGy per Gy air kerma) for HVL = 2.5 mm Al	Dose conversion factor (mGy per Gy air kerma) for HVL = 3.0 mm Al	Dose conversion factor (mGy per Gy air kerma) for HVL = 3.5 mm Al
Thyroid	Chest PA	183	35.6 × 43.2	120 (c)	--	174[c]	46	62
	Chest LAT.	183	35.6 × 43.2	--	--	--	--	151
	Stereo PFG	122	10.2 × 25.4	--	--	174[c]	--	--
	LS AP	99	35.6 × 43.2	--	0.2	--	--	--
	LS LAT.	99	35.6 × 43.2	--	0.01	--	--	--
Eye/Brain	Chest PA	183	35.6 × 43.2	11	--	32[c]	46	62
	Chest LAT.	183	35.6 × 43.2	--	--	--	--	151
	Stereo PFG	122	10.2 × 25.4	--	--	32[c]	--	--
	LS AP	99	35.6 × 43.2	--	0.2	--	--	--
	LS LAT.	99	35.6 × 43.2	--	0.01	--	--	--
Ovaries	Chest PA	183	35.6 × 43.2	N/A	--	N/A	1.8	3.2
	Chest LAT.	183	35.6 × 43.2	--	--	--	--	1.6
	Stereo PFG	122	10.2 × 25.4	--	--	N/A	--	--
	LS AP	99	35.6 × 43.2	--	N/A	--	--	--
	LS LAT.	99	35.6 × 43.2	--	N/A	--	--	--
Testes	Chest PA	183	35.6 × 43.2	N/A	--	N/A	0.01	0.01
	Chest LAT.	183	35.6 × 43.2	--	--	--	--	0.1
	Stereo PFG	122	10.2 × 25.4	--	--	N/A	--	--
	LS AP	99	35.6 × 43.2	--	N/A	--	--	--
	LS LAT.	99	35.6 × 43.2	--	N/A	--	--	--
Lungs (male)	Chest PA	183	35.6 × 43.2	243	--	419	496	565
	Chest LAT.	183	35.6 × 43.2	--	--	--	--	276
	Stereo PFG	122	10.2 × 25.4	--	--	419	--	--
	LS AP	99	35.6 × 43.2	--	62	--	--	--
	LS LAT.	99	35.6 × 43.2	--	10	--	--	--
Lungs (female)	Chest PA	183	35.6 × 43.2	250	--	451	535	610
	Chest LAT.	183	35.6 × 43.2	--	--	--	--	310
	Stereo PFG	122	10.2 × 25.4	--	--	451	--	--
	LS AP	99	35.6 × 43.2	--	62	--	--	--
	LS LAT.	99	35.6 × 43.2	--	10	--	--	--
Breast	Chest PA	183	35.6 × 43.2	18	--	49	69	91
	Chest LAT.	183	35.6 × 43.2	--	--	--	--	316
	Stereo PFG	122	10.2 × 25.4	--	--	49	--	--
	LS AP	99	35.6 × 43.2	--	18 (d)	--	--	--
	LS LAT.	99	35.6 × 43.2	--	9.5 (d)	--	--	--
Uterus (embryo)	Chest PA	183	35.6 × 43.2	N/A	--	N/A	2.3	3
	Chest LAT.	183	35.6 × 43.2	--	--	--	--	1.4
	Stereo PFG	122	10.2 × 25.4	--	--	N/A	--	--
	LS AP	99	35.6 × 43.2	--	217	--	--	--
	LS LAT.	99	35.6 × 43.2	--	20	--	--	--

Organ	View [b]	Source-image distance (cm)	Image receptor size (cm)	Dose conversion factor (mGy per Gy air kerma) for HVL = 1.5 mm Al	Dose conversion factor (mGy per Gy air kerma) for HVL = 2.0 mm Al	Dose conversion factor (mGy per Gy air kerma) for HVL = 2.5 mm Al	Dose conversion factor (mGy per Gy air kerma) for HVL = 3.0 mm Al	Dose conversion factor (mGy per Gy air kerma) for HVL = 3.5 mm Al
Bone marrow (male)	Chest PA	183	35.6 × 43.2	49	--	92	117	146
	Chest LAT.	183	35.6 × 43.2	--	--	--	--	61
	Stereo PFG	122	10.2 × 25.4	--	--	92	--	--
	LS AP	99	35.6 × 43.2	--	24	--	--	--
	LS LAT.	99	35.6 × 43.2	--	15	--	--	--
Bone marrow (female)	Chest PA	183	35.6 × 43.2	43	--	86	112	141
	Chest LAT.	183	35.6 × 43.2	--	--	--	--	48
	Stereo PFG	122	10.2 × 25.4	--	--	86	--	--
	LS AP	99	35.6 × 43.2	--	24	--	--	--
	LS LAT.	99	35.6 × 43.2	--	15	--	--	--
Skin (e)	Chest PA	183	35.6 × 43.2	1.28	--	1.36	1.39	1.41
	Chest LAT.	183	35.6 × 43.2	--	--	--	--	1.41
	Stereo PFG	122	10.2 × 25.4	--	--	1.36	--	--
	LS AP	99	35.6 × 43.2	--	1.32	--	--	--
	LS LAT.	99	35.6 × 43.2	--	1.32	--	--	--

a. Dose conversion factors (DCFs) for HVLs of 1.5, 2.0, 3.0, and 3.5 mm Al are from Tables A.2 through A.9 of ICRP 34, assuming good collimation of the beam, unless otherwise noted. The DCFs for the 2.5 mm HVL were obtained from Table 4.0-1 of ORAUT-OTIB-0006 because data indicate that the collimation may have been questionable. "N/A" means dose values represent measurements rather than DCF.
b. LS = lumbar spine.
c. Value per OTIB-0006, rev. 3 PC-1 (ORAUT 2005) assuming poor collimation of the beam.
d. Dose conversion factors for breast for lumbar spine examination not given in ICRP 34. Values for the respective upper gastrointestinal exams (i.e., AP and LAT) were used instead.
e. Values are dimensionless backscatter factors from Table B.8 of NCRP 102 (1989). Values for HVLs = 2.5 and 3.5 were obtained via linear interpolation.

Table 3-6. Organ dose estimates for ORNL chest and lumbar spine radiographs to be used as IREP inputs.[a]

Organ	View	Organ dose (rem) prior to 1947	Organ dose (rem) 1947–1963	Organ dose (rem) 1950–1953 (b)	Organ dose (rem) 1964–1990	Organ dose (rem) 1990–present	Organ dose (rem) 1996–present
Thyroid	Chest PA	3.48E-02	6.72E-03	--	5.98E-03	1.36E-03	1.36E-03
	Chest LAT.	--	--	--	--	--	9.36E-03
	Stereo PFG	4.87E-01 (d)	--	--	--	--	--
	LS AP	--	--	8.00E-04 (d)	--	--	--
	LS LAT.	--	--	1.00E-04 (d)	--	--	--
Eye/Brain	Chest PA	6.40E-03	6.16E-04	--	5.98E-03	1.36E-03	1.36E-03
	Chest LAT.	--	--	--	--	--	9.36E-03
	Stereo PFG	8.96E-02 (d)	--	--	--	--	--
	LS AP	--	--	8.00E-04 (d)	--	--	--
	LS LAT.	--	--	1.00E-04 (d)	--	--	--
Ovaries	Chest PA	2.5E-02 (c)	5E-03 (f)	--	2.34E-04	7.04E-05	7.04E-05
	Chest LAT.	--	--	--	--	--	9.92E-05
	Stereo PFG	2.5E-02 (c) (g)	--	--	--	--	--
	LS AP	--	--	1.12E+00 (d) (f)	--	--	--
	LS LAT.	--	--	1.52E+00 (d) (f)	--	--	--
Testes	Chest PA	5.0E-03 (c)	2E-03 (f)	--	1.30E-06	2.20E-07	2.20E-07
	Chest LAT.	--	--	--	--	--	6.20E-06
	Stereo PFG	5.0E-03 (c) (g)	--	--	--	--	--
	LS AP	--	--	5.40E-02 (d) (f)	--	--	--
	LS LAT.	--	--	1.12E-01 (d) (f)	--	--	--
Lungs (male)	Chest PA	8.38E-02	1.36E-02	--	6.45E-02	1.24E-02	1.24E-02
	Chest LAT.	--	--	--	--	--	1.71E-02
	Stereo PFG	1.17E+00 (d)	--	--	--	--	--
	LS AP	--	--	2.48E-01 (d)	--	--	--
	LS LAT.	--	--	1.00E-01 (d)	--	--	--
Lungs (female)	Chest PA	9.02E-02	1.40E-02	--	6.96E-02	1.34E-02	1.34E-02
	Chest LAT.	--	--	--	--	--	1.92E-02
	Stereo PFG	1.26E+00 (d)	--	--	--	--	--
	LS AP	--	--	2.48E-01 (d)	--	--	--
	LS LAT.	--	--	1.00E-01 (d)	--	--	--
Breast	Chest PA	9.80E-03	1.01E-03	--	8.97E-03	2.00E-03	2.00E-03
	Chest LAT.	--	--	--	--	--	1.96E-02
	Stereo PFG	1.37E-01 (d)	--	--	--	--	--
	LS AP	--	--	7.20E-02 (d)	--	--	--
	LS LAT.	--	--	9.50E-02 (d)	--	--	--
Uterus (embryo)	Chest PA	2.5E-02 (c)	5E-03 (f)	--	2.99E-04	6.60E-05	6.60E-05
	Chest LAT.	--	--	--	--	--	8.68E-05
	Stereo PFG	2.5E-02 (c) (g)	--	--	--	--	--
	LS AP	--	--	8.68E-01 (d)	--	--	--
	LS LAT.	--	--	2.00E-01 (d)	--	--	--
Bone marrow (male)	Chest PA	1.84E-02	2.74E-03	--	1.52E-02	3.21E-03	3.21E-03

Organ	View	Organ dose (rem) prior to 1947	Organ dose (rem) 1947–1963	Organ dose (rem) 1950–1953 (b)	Organ dose (rem) 1964–1990	Organ dose (rem) 1990–present	Organ dose (rem) 1996–present
	Chest LAT.	--	--	--	--	--	3.78E-03
	Stereo PFG	2.58E-01 (d)	--	--	--	--	--
	LS AP	--	--	9.60E-02 (d)	--	--	--
	LS LAT.	--	--	1.50E-01 (d)	--	--	--
Bone marrow (female)	Chest PA	1.72E-02	2.41E-03	--	1.46E-02	3.10E-03	3.10E-03
	Chest LAT.	--	--	--	--	--	2.98E-03
	Stereo PFG	2.41E-01 (d)	--	--	--	--	--
	LS AP	--	--	9.60E-02 (d)	--	--	--
	LS LAT.	--	--	1.50E-01 (d)	--	--	--
Skin (d)	Chest PA	2.72E-01	7.17E-02	--	1.81E-01	3.10E-02	3.10E-02
	Chest LAT.	--	--	--	--	--	8.74E-02
	Stereo PFG	3.81E+00 (d)	--	--	--	--	--
	LS AP	--	--	5.28E+00 (d)	--	--	--
	LS LAT.	--	--	1.32E+01 (d)	--	--	--

a. The exposures for various date ranges should be matched to the X-ray examinations listed in Table 3-2.
b. Applies only to preplacement exams for craft workers between 1950 and 1953. In these cases dose from the lumbar exams should be included with that from a PA chest exam for the period 1947 – 1963.
c. Default value from OTIB-0006, Rev. 3 PC-1 (ORAUT 2005).
d. Value is doubled to account for two exposures.
e. Skin dose values include backscatter factors from Table B.8 of NCRP 102 (1989).
f. Organ dose values for the testes and ovaries for lumbar spine views for 1950 – 1953 are measurements reported in Tables III and IV of Lincoln and Gupton (1957).
g. The value is not doubled because this organ should not have been in the primary beam. The value from OTIB-0006 is expected to be favorable to the claimant without the need to double it.

Table 3-7. Surrogate and associated organs.

Surrogate	Associated organs
Lung	Thymus, esophagus, stomach, liver, gall bladder, spleen, remainder, and bone surface
Ovaries	Urinary/bladder and colon & rectum

The influence of such other factors as use of screens, grids, reciprocity failure, film speed, and development, while potentially variable, would not affect the beam output 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, although output is essentially constant unless focal spot loading occurs, as might be the case if 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 might occur in line voltage input or other internal voltage of the machine. In general, for a given applied voltage setting, variation in kVp falls within ±5% (Seibert, Barnes, and Gould 1991). As noted above, beam intensity is approximately proportional to the 1.7 power of the applied voltage; this translates to an uncertainty of approximately ±8.6% with respect to output beam intensity in the 80 to 100 kVp. For conservatism, this is rounded up to ±9%.

Similarly slight variations in tube current are normal. As a tube ages, or heats 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 result in maintenance on 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. There is no evidence to suggest that such temporary measures were ever necessary or applied at ORNL. 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. 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% [11].

Another parameter that has the potential to affect dose from a radiographic procedure, 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, six pulses would result. A small error in the timer that resulted in a change of only ±1 pulse would 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. Nonetheless, the uncertainty in beam output attributable to timers was assumed to have an upper limit of ±25%.

The final factor likely to affect worker dose relates to the distance of the worker from the source of the X-rays, which is a determinant of the ESE. For a given individual, the SSD will be determined largely by the body thickness of the worker and the accuracy of the positioning. 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 of the distance, this indicates an uncertainty of ±10% from this source [12].

The combined uncertainty from the five potential sources described above was estimated by assuming that the uncertainties are random and computing the root mean square (RMS) value. The

RMS value is simply the square root of the sum of the squares and computes as ±28.8%. Rounding this value up to ±30% would seem convenient and favorable to the claimant [13].

3.5 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.

Kenny Fleming served as the initial Subject Expert for this document. Mr. Fleming was previously employed at ORNL and his work involved management, direction, or implementation of radiation protection and/or health physics program policies, procedures, or practices in relation to atomic weapons activities at the site. This revision and earlier revisions have 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 previous studies or writings are included or relied on by Mr. Fleming, those materials are fully attributed to the source.

[1] Burns, Robert E. Shonka Research Associates. Senior Health Physicist. April 2007.
The 0.04 mm Al total beam filtration asserted by the ORNL Medical Department appears to be in error because the cited total filtration is less than typical inherent filtration. A typical beam quality with an HVL of 1.5 mm Al was therefore assumed.

[2] Thomas, Elyse M. Oak Ridge Associated Universities. Principal Dosimetrist. April 2007.
Given the low asserted value, the ESE was estimated using operating parameters.

[3] Burns, Robert E. Shonka Research Associates. Senior Health Physicist. April 2007.
This conclusion was drawn from an examination of worker medical records at ORNL.

[4] Burns, Robert E. Shonka Research Associates. Senior Health Physicist. April 2007.
This conclusion was drawn from an examination of worker medical records at ORNL.

[5] Thomas, Elyse M. Oak Ridge Associated Universities. Principal Dosimetrist. April 2007.
These dimensions reflect central tendencies for these variables.

[6] Burns, Robert E. Shonka Research Associates. Senior Health Physicist. April 2007.
It is unlikely that the previous units were constant potential.

[7] Burns, Robert E. Shonka Research Associates. Senior Health Physicist. April 2007.
The assumption of two exposures per examination was made to ensure results that are favorable to the claimant.

[8] Burns, Robert E. Shonka Research Associates. Senior Health Physicist. April 2007.
This assumption was selected to ensure results that are favorable to the claimant.

[9] Burns, Robert E. Shonka Research Associates. Senior Health Physicist. April 2007.
The 0.2-rem ESE value from OTIB-0006 (ORAUT 2005) and Table 3-4 should be favorable to the claimant for any PA chest examinations before 1947; therefore, the values in Table 3-6 are

favorable for PA chest examinations performed in Knoxville or elsewhere. The 0.2 rem ESE value is derived from general medical literature of that time.

[10] Burns, Robert E. Shonka Research Associates. Senior Health Physicist. April 2007. The 0.2-rem ESE value from OTIB-0006 (ORAUT 2005) is derived from general medical literature of that time. Organ dose values computed using this value should be favorable to the claimant for any PA chest examinations performed prior to October, 1947.

[11] Burns, Robert E. Shonka Research Associates. Senior Health Physicist. April 2007. An uncertainty of ±5% should encompass any real variability in tube current.

[12] Burns, Robert E. Shonka Research Associates. Senior Health Physicist. April 2007. The assumption of a 7.5-cm SSD variation, which is at the upper end of any variation that would be expected to occur with the use of prudent technique, was selected to ensure favorability to the claimant.

[13] Burns, Robert E. Shonka Research Associates. Senior Health Physicist. April 2007. Selection of the RMS value of uncertainty reflects accepted practice.

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GLOSSARY

beam quality

The beam quality is used to describe the "hardness" of the X-ray beam. Hardness is increased by inserting filtration (typically aluminum) between the X-ray source and subject. Hardening the beam removes low-energy photons, thereby reducing the patient's skin exposure, while preserving the higher-energy photons needed for imaging.

collimation

Was used to focus and minimize the secondary and scattered photons that may irradiate other organs that are not important for diagnosis. A 20-cm cone was used early at ORNL to reduce this scatter.

photofluorography (PFG)

A chest X-ray examination given at the Oak Ridge Hospital prior to X-ray equipment being acquired and used at ORNL. The PFG films seen at ORNL were 4" × 10" films showing two chest films that could be reviewed by a radiologist to see 3-D views of an individual's chest. The films were not X-ray films but were captured by taking two pictures with a camera of an image-intensifying screen.

termination examination

A medical examination provided upon an employee's release from ORNL.