ORAU Team **Dose Reconstruction Project for NIOSH** Technical Basis Document for the Oak Ridge National Laboratory – Occupational Medical Dose	Document Number: ORAUT-TKBS-0012-3 Effective Date: 07/21/2006 Revision No.: 01 PC-1 Controlled Copy No.:_____ Page 1 of 27
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RECORD OF ISSUE/REVISIONS

ISSUE AUTHORIZATION DATE	EFFECTIVE DATE	REV. NO.	DESCRIPTION
04/20/2004	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	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.
10/29/2004	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

ACRONYMS AND ABBREVIATIONS

Al	aluminum
AP	anterior-posterior (front-to-back) view
cGy	centigray
cm	centimeter
DCF	dose conversion factor
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	peak applied voltage (in kilovolts)
Lat or Lateral	Lateral (or side) view
mA	milliampere
mAs	milliampere-second
mm	millimeter
mrad	millirad
NBS	National Bureau of Standards (later National Institute of Standards and Technology)
NCRP	National Council on Radiation Protection and Measurements
NIOSH	National Institute for Occupational Safety and Health
ORNL	Oak Ridge National Laboratory
ORR	Oak Ridge Reservation
PA	posterior-anterior (back-to-front) view
PFG	photofluorography
R	Roentgen
RMS	root mean square
SID	source-to-image distance
SSD	source-to-skin distance
X-10	The Oak Ridge National Laboratory site
Y-12	The Y-12 National Nuclear Security Complex

3.1 INTRODUCTION

Technical basis documents and site profile documents are general working documents that provide guidance concerning the preparation of dose reconstructions at particular sites or categories of sites. They will be revised in the event additional relevant information is obtained about the affected site(s). These documents may be used to assist the National Institute for Occupational Safety and Health (NIOSH) 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.

3.2 PURPOSE

Diagnostic 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 the Energy Employees Occupational Illness Compensation Program Act of 2000 (EEOICPA). Unlike occupational exposures incurred during normal work processes, individual diagnostic medical X-ray exposures were not monitored, necessitating the use of the information provided in this document in the reconstruction of acquired exposures.

3.3 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) as a condition of employment at ORNL. Relatively high-exposure-producing photofluorographic (PFG) techniques were used from 1943 through October 3, 1947, to conduct preplacement chest examinations for potential ORNL workers.

3.4 TECHNICAL FACTORS AFFECTING DIAGNOSTIC X-RAY DOSE

A number of factors affect doses to workers from diagnostic X-ray procedures. For a standard medical radiographic (i.e., diagnostic) 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.

3.4.1 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 between the beam and the targeted area. 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 eliminate 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 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 diagnostic 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. The total filtration given for this device was found documented (Lincoln and Gupton 1958a and 1958b) as 1 mm Al and was used to estimate the entrance skin exposure[2] (ESE) values for lumbar spine X-ray examinations for the instrument used between 1947 to 1963. The documented skin exposure in these same reports was low (21 mrad) for the PA chest X-ray examination as compared to skin exposures from other chest X rays given during that timeframe. The skin exposure for that timeframe was estimated using operating parameters.

Although the benefits of filtration with respect to improved radiographic images were known and understood as early as March 1896, within months of the discovery of X-rays (Magie 1896), diagnostic 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

[2] Throughout this document, *italics* will be 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.

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 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:

$$I = I_o e^{-0.4t}$$

or

$$\ln (I/I_o) = -0.4\ t$$

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 2002), 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 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 (2002), can be applied to determine the effect of applied voltage on beam intensity.

3.4.2 Current and Exposure Time

Diagnostic 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

[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, 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.

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, from a dose reconstruction standpoint, 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 diagnostic X-ray machine in early October 1947. It was stated by the Radiology Technician that 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. 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. 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. (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 gastro-intestinal examinations.)

3.4.3 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). The distance to the worker, who was between the source and the film cassette, 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. In addition, patient size can further reduce or attenuate the number of photons that can pass through the worker and reach the film. To compensate for the increased attenuation and scattering of X-rays provided by a larger worker, X-ray technicians would sometimes increase the beam settings or, if the machine was so equipped, might use a high-speed Potter-Bucky diaphragm, probably with a somewhat higher applied voltage. Therefore it might be appropriate for an individual dose reconstruction to increase the ESE for a large or stout worker if this information is known. Based on standard contemporary techniques (Picker 1941; Fuchs 1958; Cahoon 1961) for workers with a chest thickness of 25 to 27 cm, an

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

increase of +50% from the ESE to the average worker should be sufficient; for still larger workers, a factor of 2 would be appropriate. [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.)

3.4.4 Waveform and Collimation Characteristics

Among other factors that could affect worker dose are waveform and collimation. X-ray waveforms are of three types: half-wave rectified, which were present in the earliest X-ray equipment; full-wave rectified; and constant potential. A half-wave rectified machine produces 60 half-sinusoidal shaped pulses of X-rays per second, each with a duration of 1/120 of a second. A full-wave rectified machine produces 120 half-sinusoidal pulses per second, each with a 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. A constant potential machine produces a more or less steady (i.e., unpulsed) output of X-rays and has a somewhat greater beam intensity – approximately 10% more – than a full-wave rectified machine operating at the same kVp and mA. (It was assumed that single phase units were used until 1990 when a constant potential unit was procured for ORNL.)

Collimation refers to the size of beam and how it is focused on the target area. 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 patient 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 or penumbra effect 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 1958a) indicates that a 20 cm cone was used in the mid 1950s at ORNL to reduce secondary photons and therefore to collimated the primary beam. Results given in a table (Lincoln and Gupton 1958a) indicate that the dose conversion factors (DCFs) given in ICRP 34 for a well collimated beam may not apply and therefore uncollimated DCFs found in ORAUT-OTIB-0006, Table 4.0-1 (ORAU 2003), were used until a newer X-ray unit was procured in 1963. Another document from the same author (Lincoln and Gupton 1958b) stated that “Gonad doses determined from these phantom measurements are probably exaggerated, as the phantom is somewhat smaller than the average adult.”

3.4.5 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. However, the factors can be used as additional confirmation of the applicability of the reconstructed dose. 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 diagnostic 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 diagnostic 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.

3.5 DIAGNOSTIC X-RAY DOSES TO ORNL WORKERS, 1943 TO PRESENT

For convenience and possible application to cases in which the standard ORNL protocol was not followed, or for generic use, 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
Worker size (chest thickness)	25-27 mm > 27 mm	Dose increased by factor of 1.5 Dose increased by factor of 2
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 techniques 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. 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 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. 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 images.

[However, during the review of radiographic images archived by the ORNL medical department, two stereo PFG films were located for an individual that were taken approximately 1 year apart. The initial PFG was followed approximately 2 weeks later with a 14- × 17-in. radiographic PA 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. As needed, follow-up examinations with conventional-sized films (e.g., 14- × 17-in.) were taken 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 diagnostic 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 at a Knoxville hospital would be claimant-favorable, 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. [The United States Army Center for Health Protection and Preventative Medicine (USACHPPM) 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 employment conducted in the ORNL Medical area used conventional, diagnostic 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 K. Z. Morgan’s request, 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) shots. 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 collimation of the X-ray beam.

Table 3-2 lists radiographic examinations that would be considered occupational medical exposures 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 between the beam source and target to harden it. The exposure time of 0.01 sec with a tube current of 300 mA gives a 3-mAs intensity, which was believed to be low for that period. Rather than using the given 0.01-sec exposure time, it is assumed that the exposure time was 0.1 sec, making exposures for PA chest films 30 mAs when using the Picker X-ray unit. The radiology 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 techniques, 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 instruments 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 preplacement, routine annual, and termination radiographic chest examinations 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 accurately estimate an individual's occupational medical X-ray examination record from October 3, 1947. 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 and 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 claimant favorable.

Field surveys provided by the ORNL RT at the Oak Ridge Hospital indicated that the skin exposure for a single exposure PA Chest PFG was 1.4 R (or 2.8 R for the 2 PA Chest PFG exposures). This value should be used for individuals whose medical records indicate a preplacement chest X-ray examination prior to October 3, 1947, unless the records indicate that a PFG exam was not used. In addition, the ESE and organ dose values provided for PFG exams should be divided by 2 if it is known that only a single PFG exposure was made. Any confirmed retake, annual, or termination chest X-ray exams should assume that standard 14- × 17-in. PA films were made unless otherwise noted in the medical records. Organ doses have been provided for each of these cases.

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). Nonetheless, regulations applicable to ORNL and other DOE sites defined 1 R as exactly equal to a dose of 1 rad (10 mGy), thereby producing an overestimate in the reported dose or dose equivalent because dosimeters were typically calibrated against a field measured in R, which was numerically equated as absorbed dose in rad (Kathren and Petersen 1989). 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 examination technique used at ORNL are listed in Table 3-4. If measured ESE data were not obtained from 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 (1958a and 1958b) 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. 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 survey of the Hospital's PFG unit indicated an exposure to the skin of 1.4 R. The ESE values for examinations at Oak Ridge Hospital of 2.8 R and 0.2 R are to be used for stereo PFG (two exposures) and PA chest procedures, respectively.] The skin exposure value of 1.4 R was obtained from the survey conducted in 1956 of the PFG unit at the Oak Ridge Hospital and assumed to be the claimant favorable value used for the ESE. This value was doubled to 2.8 to account for two PFG exposures. An ESE value of 0.2 R should be used for each radiographic PA chest examination noted for an individual prior to examinations conducted at ORNL in October 1947, and for any PA chest examination after this time that is known to have occurred outside the ORNL Medical department (unless a better-known ESE value is available for the outside examination).

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 (ORAU 2003) 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 ORAU COC Medical X-ray Lead to estimate and verify the values used in Table 3-5 of this report.] These tables 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 (ORAU 2003). Thus, the factor for lung should be 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 should also be 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 should be 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 could be 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 ORAU (2003).

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 ORAU (2003) 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. In addition, since there are no DCFs for female breasts given for the AP and Lateral lumbar spine examinations, the DCFs for the similar Upper GI projections were used to estimate organ dose. Table A6 in ICRP 34 states that for lumbar spine exams, DCFs were "Not computed but small compared with projections listed above." The use of the Upper GI DCFs should therefore be claimant favorable.

3.6 UNCERTAINTY ANALYSIS FOR ORNL RADIOGRAPHY DOSES

In theory a large number of factors can introduce uncertainties or affect the X-ray machine output intensity and dose to the worker. Occupational medical X-ray exposures (e.g., ESEs) at ORNL were derived from equipment operating factors. Several factors can have an impact on dose uncertainty:

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)

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 voltages, which in turn could alter the applied voltage of the output beam. In general, for a given applied voltage setting, variation in kVp falls within ±5% of the machine setting (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%.

Another parameter that has potential to affect the dose from a diagnostic radiograph, 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.

The combined uncertainty from the five potential sources described above was estimated by assuming that the uncertainties are random and compute 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.

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

Dates	X-ray equipment	Location	Techniques	X-ray conditions	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), PA chest X-ray (possibly others)	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		

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 documents (1958a and 1958b) 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.
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 increased to 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 shield 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 uncollimated DCFs 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 values 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 (1958a) indicates 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 claimant favorable.
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).

Table 3-5. Average absorbed dose per unit entrance air kerma for selected X-ray views, 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)	21	174	46	62
	Chest Lat.	183	35.6 × 43.2	--	--	--	--	151
	Stereo PFG	122	10.2 × 25.4	--	--	174	--	--
	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	21	32	46	62
	Chest Lat.	183	35.6 × 43.2	--	--	--	--	151
	Stereo PFG	122	10.2 × 25.4	--	--	32	--	--
	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	0.6	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	0.01	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	335	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	355	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	32	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	0.7	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	--	--	--

Table 3-5 continued

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	69	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	63	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	--	--	--
Total body (male)	Chest PA	183	35.6 × 43.2	83	108	131	153	174
	Chest Lat.	183	35.6 × 43.2	--	--	--	--	94
	Stereo PFG	122	10.2 × 25.4	--	--	131	--	--
	LS AP	99	35.6 × 43.2	--	83	--	--	--
	LS Lat.	99	35.6 × 43.2	--	38	--	--	--
Total body (female)	Chest PA	183	35.6 × 43.2	66	93	118	140	161
	Chest Lat.	183	35.6 × 43.2	--	--	--	--	89
	Stereo PFG	122	10.2 × 25.4	--	--	118	--	--
	LS AP	99	35.6 × 43.2	--	83	--	--	--
	LS Lat.	99	35.6 × 43.2	--	38	--	--	--
Skin (e)	Chest PA	183	35.6 × 43.2	1.28	1.32	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 or default values rather than product of ESE and DCF.
b. LS = lumbar spine.
c. Value per OTIB-0006, rev. 2 (ORAU 2003) due to questionable collimation of the beam.
d. Dose conversion factors for lumbar spine examination not given in ICRP 34. Values for the respective Upper G.I. 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	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	--
	Chest Lat.	--	--	--	--	--	9.36E-03
	Stereo PFG	4.87E-01 (c)	--	--	--	--	--
	LS AP	--	--	8.00E-04 (c)	--	--	--
	LS Lat.	--	--	1.00E-04 (c)	--	--	--
Eye/Brain	Chest PA	6.40E-03	6.16E-04	--	5.98E-03	1.36E-03	--
	Chest Lat.	--	--	--	--	--	9.36E-03
	Stereo PFG	8.96E-02 (c)	--	--	--	--	--
	LS AP	--	--	8.00E-04 (c)	--	--	--
	LS Lat.	--	--	1.00E-04 (c)	--	--	--
Ovaries	Chest PA	2.5E-02 (b)	5E-03 (e)	--	2.34E-04	7.04E-05	--
	Chest Lat.	--	--	--	--	--	9.92E-05
	Stereo PFG	5.0E-02 (b) (c)	--	--	--	--	--
	LS AP	--	--	1.12E+00 (c) (e)	--	--	--
	LS Lat.	--	--	1.52E+00 (c) (e)	--	--	--
Testes	Chest PA	5.0E-03 (b)	2E-03 (e)	--	1.30E-06	2.20E-07	--
	Chest Lat.	--	--	--	--	--	6.20E-06
	Stereo PFG	1.0E-02 (b) (c)	--	--	--	--	--
	LS AP	--	--	5.40E-02 (c) (e)	--	--	--
	LS Lat.	--	--	1.12E-01 (c) (e)	--	--	--
Lungs (male)	Chest PA	8.38E-02	1.36E-02	--	6.45E-02	1.24E-02	--
	Chest Lat.	--	--	--	--	--	1.71E-02
	Stereo PFG	1.17E+00 (c)	--	--	--	--	--
	LS AP	--	--	2.48E-01 (c)	--	--	--
	LS Lat.	--	--	1.00E-01 (c)	--	--	--
Lungs (female)	Chest PA	9.02E-02	1.40E-02	--	6.96E-02	1.34E-02	--
	Chest Lat.	--	--	--	--	--	1.92E-02
	Stereo PFG	1.26E+00 (c)	--	--	--	--	--
	LS AP	--	--	2.48E-01 (c)	--	--	--
	LS Lat.	--	--	1.00E-01 (c)	--	--	--
Breast	Chest PA	9.80E-03	1.01E-03	--	8.97E-03	2.00E-03	--
	Chest Lat.	--	--	--	--	--	1.96E-02
	Stereo PFG	1.37E-01 (c)	--	--	--	--	--
	LS AP	--	--	7.20E-02 (c)	--	--	--
	LS Lat.	--	--	9.50E-02 (c)	--	--	--
Uterus (embryo)	Chest PA	2.5E-02 (b)	5E-03 (e)	--	2.99E-04	6.60E-05	--
	Chest Lat.	--	--	--	--	--	8.68E-05
	Stereo PFG	5.0E-02 (b) (c)	--	--	--	--	--
	LS AP	--	--	8.68E-01 (c)	--	--	--
	LS Lat.	--	--	2.00E-01 (c)	--	--	--
Bone marrow (male)	Chest PA	1.84E-02	2.74E-03	--	1.52E-02	3.21E-03	--
	Chest Lat.	--	--	--	--	--	3.78E-03
	Stereo PFG	2.58E-01 (c)	--	--	--	--	--
	LS AP	--	--	9.60E-02 (c)	--	--	--
	LS Lat.	--	--	1.50E-01 (c)	--	--	--

Table 3-6 continued

Organ	View	Organ dose (rem) prior to 1947	Organ dose (rem) 1947–1963	Organ dose (rem) 1950–1953	Organ dose (rem) 1964–1990	Organ dose (rem) 1990–present	Organ dose (rem) 1996–present
Bone marrow (female)	Chest PA	1.72E-02	2.41E-03	--	1.46E-02	3.10E-03	
	Chest Lat.	--	--	--	--	--	2.98E-03
	Stereo PFG	2.41E-01 (c)	--	--	--	--	--
	LS AP	--	--	9.60E-02 (c)	--	--	--
	LS Lat.	--	--	1.50E-01 (c)	--	--	--
Total body (male)	Chest PA	2.62E-02	4.65E-03	--	1.99E-02	3.83E-03	--
	Chest Lat.	--	--	--	--	--	5.83E-03
	Stereo PFG	3.67E-01 (c)	--	--	--	--	--
	LS AP	--	--	3.32E-01 (c)	--	--	--
	LS Lat.	--	--	3.80E-01 (c)	--	--	--
Total body (female)	Chest PA	2.36E-02	3.70E-03	--	1.82E-02	3.54E-03	--
	Chest Lat.	--	--	--	--	--	5.52E-03
	Stereo PFG	3.30E-01 (c)	--	--	--	--	--
	LS AP	--	--	3.32E-01 (c)	--	--	--
	LS Lat.	--	--	3.80E-01 (c)	--	--	--
Skin (d)	Chest PA	2.72E-01	7.17E-02	--	1.81E-01	3.10E-02	--
	Chest Lat.	--	--	--	--	--	8.74E-02
	Stereo PFG	3.81E+00 (c)	--	--	--	--	--
	LS AP	--	--	5.28E+00 (c)	--	--	--
	LS Lat.	--	--	1.32E+01 (c)	--	--	--

a. The exposures for various date ranges should be matched to the X-ray examinations listed in Table 3-2.
b. Default value from OTIB-0006, rev. 2 (ORAU 2003).
c. Value is doubled to account for two exposures.
d. Skin dose values include backscatter factors from Table B.8 of NCRP 102 (1989).
e. 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 (1958b).

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

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GLOSSARY

beam quality

The beam quality is used to describe the “hardness” of the X-ray beam. The beam quality is increased by inserting filtration (typically Aluminum shielding) between the X-ray source and target. The addition of filtration is used to shield much of the useless, low energy photons and typically increases the resulting film.

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.