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PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
06/09/2004	00	New technical basis document for the Nevada Test Site – Occupational Medical Dose. Incorporates internal review and NIOSH comments. First approved issue. Initiated by Eugene M. Rollins.
06/22/2007	01	Approved revision initiated to concur with ORAUT-OTIB-0006 (ORAUT 2005), current data in other TBDs, and to include new legal wording in Section 3.1. Constitutes a total rewrite of the document. Incorporates formal internal and NIOSH review comments. Adds Attributions and Annotations section. This revision results in no change to the assigned dose and no PER is required. Training required: As determined by the Task Manager. Initiated by Vernon E. Shockley.

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ACRONYMS AND ABBREVIATIONS

CFR	Code of Federal Regulations
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 Radiation Units and Measurements
in.	inch
IREP	Interactive RadioEpidemiological Program
keV	kiloelectron-volt, 1,000 electron-volts
kVp	peak kilovoltage, applied kilovoltage
LAT	lateral
mA	milliampere
mAs	milliampere-second
mGy	milligray
mm	millimeter
mm Al	millimeters of aluminum
mrad	millirad
mR	milliroentgen
mrem	millirem
NCRP	National Council on Radiation Protection and Measurement
NIOSH	National Institute for Occupational Safety and Health
NTS	Nevada Test Site
ORAU	Oak Ridge Associated Universities
PA	posterior–anterior
POC	probability of causation
R	roentgen
RMS	root mean square
s	second
SID	source-to-image distance
SRDB Ref ID	Site Research Database Reference Identification (number)
SSD	source-to-skin distance
TBD	technical basis document

U.S.C.	United States Code
§	section or sections

3.1 INTRODUCTION

Technical basis documents and site profile documents are not official determinations made by the National Institute for Occupational Safety and Health (NIOSH) but are rather general working documents that provide historic background information and guidance to assist in the preparation of dose reconstructions 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

The purpose of this TBD is to describe Nevada Test Site (NTS) occupational medical X-ray systems and practices. The Oak Ridge Associated Universities (ORAU) Team will use this information as needed to evaluate medical X-ray doses for EEOICPA claims.

3.1.2 Scope

This TBD describes the technical aspects of dose reconstruction from medical X-rays administered prior to employment and periodically thereafter as a condition of employment.

Attributions and annotations, indicated by bracketed callouts and used to identify the source, justification, or clarification of the associated information, are presented in Section 3.5.

3.2 TECHNICAL FACTORS THAT AFFECT MEDICAL X-RAY DOSE

A number of factors determine the dose to workers from a medical X-ray procedure. For a standard medical radiographic unit with a tungsten target (anode) and focal spot of 1 to 2 mm, these factors include the basic machine settings used for the exposure, which include the applied kilovoltage of the beam (kVp, also known as peak kilovoltage), beam current in milliamperes, time of exposure in seconds, distance in centimeters, waveform, amount and kind of filtration used, collimation or use of diaphragms, tube housing characteristics, type and speed of the film, development procedures, screens, grids, and the size of the worker. In the absence of direct measurements of the beam itself (which are rarely available), the dose to the worker can be estimated with a reasonable degree of accuracy from knowledge of the following three basic machine parameters: (1) applied kilovoltage, 2) current, and 3) exposure time with assumptions about filtration, collimation, and waveform characteristics ORAUT (2005). The following sections discuss the implications of these factors to worker dose. However, if X-ray exposure or dose measurements are available, as they are for some NTS procedures, these should be used in the development of organ doses.

3.2.1 Applied Kilovoltage and Filtration

The energy of the X-ray beam, sometimes referred to as beam quality, is determined by the applied kilovoltage and the filtration. X-rays produced in a typical medical X-ray tube are bremsstrahlung and, as such, are a distribution or spectrum of energies ranging from zero to the applied kilovoltage, which refers to the potential between the anode and cathode of the tube. For a typical unfiltered X-ray spectrum, the average energy is about one-third of the peak or maximum X-ray energy, which is equal to the applied kilovoltage. Therefore, most of the produced X-rays are much lower in energy than the applied kilovoltage of the beam. In addition, they are attenuated by the torso or other portion of the body being radiographed, and most never reach the film. These low-energy X-rays are of little value in radiography but contribute significantly to worker dose BRH (1970, pp. 159–160).

To reduce the dose to the worker, filtration in the form of a specified thickness of absorbing material is added to the beam port. This has the net effect of absorbing 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, the dose to the worker is reduced significantly and radiographic quality can be enhanced. A filtered X-ray spectrum has a correspondingly higher average energy than before it was filtered, even though the photon fluence rate and corresponding dose rate is much reduced. Such a beam is said to have been *hardened*. A corollary to this filtration technique is to use a higher applied kilovoltage and to filter the beam relatively heavily to stop most of the low-energy (radiographically useless) photons from reaching the worker (ICRP Publication 34; ICRP 1982, p. 25, Tables A2–A8).

Beam energy is specified in terms of quality, or hardness, which in turn, can be specified in terms of the half-value layer (HVL) in millimeters of aluminum (mm Al). This parameter is, unfortunately, 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 or its true quality because, as the HVL measurement is made, the absorbers act as filters and the beam is further hardened. Therefore, the first HVL is always smaller than the second, which in turn is smaller than the third, and so forth. What is commonly, but not always available is the peak or applied kilovoltage of the machine and the external or added filtration. All X-ray tubes have so-called inherent filtration, which is the window, aperture, or port in the tube enclosure through which the X-ray beam emerges from the X-ray tube. In medical diagnostic units, the window or beam port is purposely made very thin, typically equivalent to 0.5 mm Al in attenuation, which provides little beam hardening. Other than the beam port itself, the tube housing is shielded to eliminate leakage radiation from the tube. Therefore, the beam port effectively characterizes what could be considered the inherent collimation of the tube (DeMarre 2002; Geiger et al. 1960).

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)], initial diagnostic radiographs were made with no added filtration. Recommendations made in 1937 by the International Commission on Radiation Units and Measurements, although not specific for thickness, specified aluminum filters for X-rays of 20 to 120 kVp (which incorporates the diagnostic X-ray energy range) (ICRU 1937). Typical external filtration in the 1940s ranged from none to 1 mm Al. This was in line with recommendations of the U.S. Advisory Committee on X-Ray and Radium Protection [later the National Council on Radiological Protection and Measurement (NCRP)], which called for 0.5 mm Al 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 (NBS 1949); this thickness was used during World War II in 100-mA units in larger military hospitals, and presumably at NTS as well (Olson, Trask, and Dessen 1966). Recommended thicknesses were later increased not only for worker protection but also for improved radiographic image quality. In 1955, the NCRP recommendation for diagnostic X-ray units called for 2-mm Al filtration for new machines (NBS 1955). This increased in 1968 to 2.5 mm Al for medical diagnostic units above 70 kVp (NCRP 1968). For operating machines, these recommended filter thicknesses might not have been implemented for some time after the date of the recommendation, especially if the installed machines did not exhibit changes in effectiveness and continued to operate without apparent problems.

The relationship of beam intensity[2] to peak kilovoltage and filtration is complex and to some extent machine-specific. Therefore, the relationship is best determined empirically. However, in the absence of empirical data for a specific machine, adequate contemporary empirical and theoretical data exist on which to determine machine output with a reasonable degree of uncertainty. Additional filtration reduces the entrance skin *exposure*[3] (ESE) in a generally 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). Therefore, the approximate intensity reduction afforded by any thickness of Al filtration can be determined by the following exponential equation:

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[2] In this document, beam intensity refers to the output of the machine in terms of *exposure* in the special sense per milliampere-second. *Exposure* in the special sense is referenced to ionization in air and, as such, is not a dose quantity.

[3] Throughout this document, italics are used to differentiate *exposure* in the special sense from exposure in the general sense. A brief discussion of both the general and special senses can be found in many publications including NCRP (1985) and ICRU (1998). The definition and application of the quantity *exposure* and its concomitant unit the roentgen have undergone several important modifications over the years, which have been documented throughout the literature.

$$I = I_o e^{-0.4t} \tag{3-1}$$

or

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

where

t = mm Al
I = beam intensity with filter
I_o = beam intensity without filter

In the absence of specific measurements or empirical data, this correction can be applied to determine the effect of filtration on beam intensity, and is consistent with the guidance put forth in OCAS-IG-001, *External Dose Reconstruction Implementation Guideline* (NIOSH 2006).

Increasing the kilovoltage 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, and the best results are approximations. However, many empirical studies of beam intensity as a function of kilovoltage provide ample credible evidence to show that, for a given amount of filtration, increasing the applied kilovoltage 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 can be applied to determine the effect of applied kilovoltage on beam intensity. This method is fully consistent with the guidance in OCAS-IG-001 (NIOSH 2006).

It should be noted that the effects of filtration and applied kilovoltage tend to offset one another; addition of filtration reduces the *exposure* or dose per milliampere-seconds, while increasing the applied kilovoltage increases the *exposure* and dose per milliampere-second. Higher applied kilovoltage radiographic techniques typically require shorter exposures in terms of milliampere-seconds, and the dose reduction from additional filtration at the recommended level more than offsets the additional dose from using increased applied kilovoltage. However, there is no direct correspondence or proportionality between the effects of filtration and applied kilovoltage (Trout, Kelley, and Cathey 1952; ORAUT 2005).

3.2.2 Current and Exposure Time

X-ray exposures are typically specified in terms of milliampere-seconds, the product of X-ray tube current and exposure time. Therefore, other factors remaining equal (e.g., kilovoltage, filtration, film, development, and screen combination), radiation exposure is proportional to the number of milliampere-seconds. The current in an X-ray tube refers to the number of electrons accelerated across the evacuated volume of the tube and flowing from the cathode to the anode. In theory, the number of X-ray photons produced (and therefore the exposure) will be directly proportional to the X-ray tube current for a given applied kilovoltage. This is and has been true for most medical radiography units over their design tube current range (Gray 1996; Sante 1946, 1954; Thomas 1959; ORAUT 2005). Data from beam measurements made with medical X-ray units at NTS over the years are indicative of this linearity. Therefore, in the absence of measurements before 1957 or other information to the contrary, it is reasonable and consistent with long-standing radiographic practice (Sante 1946, p.61) to assume linearity of exposure with tube current for a given applied kilovoltage and filtration [1].

Exposure time is the time that the tube was energized (i.e., 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, the exposure time for chest radiography was minimized, and the current proportionately increased to obtain the desired exposure. However, earlier medical radiographic units were equipped with mechanical timers with accuracy that was not as good as the electronic timers used on later machines. Gross bias errors in timer accuracy are unlikely because they would have resulted in an over- or underexposure of the radiograph and so would have been quickly detected and corrected. Subtler are small random errors that can produce uncertainties of perhaps ±20% in the exposure [2]. However, the limited measurement data available from NTS medical X-ray units give no indication or suggestion that time or exposure parameters might be subject to error. No evidence has been found to suggest or verify that chest photofluorography, which resulted in much greater doses than a standard radiographic procedure, was performed for the NTS workers [3].

3.2.3 Distance

X-ray beam intensity is a function of distance from the target and approximates 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 refers to the plane of the film. The distance to the worker, sometimes expressed in terms of the source-to-skin distance (SSD), who was between the source and the film cassette, was somewhat smaller and, therefore, the ESE to the worker was somewhat greater than the exposure at the plane of the film. In addition, worker attenuation would further reduce or attenuate the number of photons that reached the film (Sante 1954; Geiger et al. 1960).

To compensate for the increased attenuation 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 (known as a Bucky), probably with a somewhat higher applied kilovoltage. However, because chest thickness is rarely recorded at the time of each X-ray, organ dose reconstruction is based on the average worker's chest size, which is 22 to 24 cm (DeMarre 2002–2003; Sante 1946,1954).

3.2.4 Collimation and Waveform Characteristics

Collimation and waveform characteristics are among the factors that affect dose. X-ray waveforms used in medical screening were half-wave rectified, which is almost never seen, and full-wave rectified, which is typical of medical radiographic units and characteristic of the units used at NTS [4]. A half-wave rectified machine produces 60 half-sinusoidal 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 of a second. Therefore, for a given setting of applied kilovoltage and milliamperes, the intensity of the beam from a half-wave rectified machine is half that of the beam from a full-wave rectified machine (Sante 1946, 1954). A third waveform, constant potential, was available at the time of initial operation at the NTS and is defined in NCRP Report 33 (NCRP) 1968. The constant potential waveform machine was not used at the NTS [5].

For NTS, waveform is of minor significance in relation to reconstruction of worker exposure because actual output measurement data are available from 1957 to 1992 [6]. Before 1957, machine techniques are not available, and estimates of X-ray exposures are based on references providing median dose for 1950 to 1957 (Gray 1996).

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

Collimation refers to the size of the beam. Early radiographic practices used a fairly large aperture with limited collimation to ensure that the radiograph included the entire area of interest. Later, because of protection concerns, beams were collimated so the smallest beam consistent with the area of interest was used, which thereby limited the exposed area of the worker and, in the case of chest radiography, lowered doses 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 leaves a small unexposed area at the edges of the radiograph, while a poorly collimated beam produces a radiograph that is exposed over all of its area (Geiger et al. 1960; DeMarre 2002–2003). Available data, including direct beam measurements, indicate that X-ray beams used at NTS were well collimated (Kathren and Shockley 2003). However, this analysis includes the favorable to claimant assumption that minimal collimation occurred before January 1, 1957. Therefore, the substitute dose conversion factors (DCFs) in Table 3-5 were used to estimate organ doses prior to January 1, 1957. (See Section 3.3 and Table 3-6) (Taulbee 2004).

3.2.5 Screens, Grids, and Other Factors That Can Affect 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 not necessary for dose reconstruction if beam measurements are available or if the primary machine characteristics of applied kilovoltage, exposure time, and current are known, along with the amount of primary beam filtration. For completeness, this document briefly mentions these factors, which are tube housing, film type, film speed, development procedure, screens, and grids.

X-ray tubes used for medical radiography are typically enclosed in protective lead or shielded tube housings with the primary beam brought out through a port or window in the side of the housing. Although some reduction of the dose to the worker is achieved, largely through elimination of scattered radiation and improved collimation, the primary purpose of this 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 NTS, had protective tube housings (DeMarre 2002, 2002–2003).

The amount of exposure needed for a suitably exposed radiograph is affected by film speed and development. Fine-grained (slow) emulsions produce a superior radiographic image but require additional exposure in comparison to course-grained (fast) films. In addition, underdevelopment of film requires additional exposure to achieve satisfactory radiographic quality. Intensifying screens are used within the cassette to intensify the radiographic effect and thereby increase film speed and reduce worker dose. Grids, specifically the Potter-Bucky diaphragm or grid (colloquially known as the Bucky), are sometimes used for thick-section radiography but rarely for chest radiography, except with large workers (Sante 1954, pp. 212–224a; Thomas et al. 1959).

For convenience and possible application to cases, Table 3-1 lists the effects of various technique factors on beam intensity. However, all of the parameters discussed in this section are factored into the technique (i.e., applied kilovoltage and current) that is used and, with the exception of rare instances and a virtually complete absence of other data, are not important to dose reconstruction NIOSH (2006).

Table 3-1. Relationship of beam intensity and various technique factors.[a]

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 cm >27 cm	ESE increased by factor of 1.5 ESE increased by factor of 2
Distance	cm	Approximately inverse square relations ($1/d^2$)
Uncertainty	±30%	Assume all errors are positive, +30% should be used

a. Source ORAUT (2005)

3.3 X- RAY DOSES FROM 1951 TO PRESENT

Extensive review of available documentation on the occupational medical program at NTS from 1951 to the present revealed that two medical radiographic procedures were commonly administered in connection with preemployment, periodic, or postemployment medical examinations:

1. 14- by 17-in. posterior-anterior (PA) chest films
2. 14- by 17-in. lateral (LAT) chest films

Therefore, this analysis evaluated only doses from these two examinations (DeMarre 2002). Some of the claim file records have lumbar spine exams that may also have been performed for screening (especially during pre-employment physicals) as opposed to injury. Organ doses for lumbar spine exams can be found in ORAU-OTIB-0006 (ORAUT 2005). Other possible radiographic examinations of NTS employees may have been nonoccupational in the sense that they were necessitated by illness or injury, as many workers lived on site and were not part of the employee physical examination process DeMarre (2002). Information from NTS indicates that X-rays performed as a result of workplace accidents were administered offsite, by private contractors in the early years, before 1960 (Kathren and Shockley 2003). Also, there is no indication that radiological treatment for shrinkage of lymphoid tissue was ever performed on NTS workers [7].

A potential problem common to all procedures relates to the conversion of *exposure* represented by ESE to absorbed organ dose as well as to changes in the definition of *dose* and the creation of numerous dose quantities. Over the 50 or so years since the beginning of NTS 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 itself is obsolete. Thus, there is much confusion about the definition of *exposure* and the roentgen. At one time, the roentgen was used to quantify the dose from electromagnetic radiation 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 (Kathren and Peterson 1989).

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 would be equated to a soft tissue dose of 0.83, 0.877, or 0.93 rad. Therefore, an *exposure* in air of 1 R would result in an absorbed dose of somewhat less than 1 rad (1 cGy = 10 mGy). Nonetheless, external dosimetry regulations applicable to NTS and other DOE sites defined 1 R as exactly equal to a dose of 1 rad (10 mGy =1 rem), thereby producing an overestimate in the reported dose or dose equivalent because dosimeters were typically calibrated against a field measured in roentgen, which was numerically equated to absorbed dose in rad (Kathren and Petersen 1989).

A further complication in 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. The numerical value of kerma is, typically, slightly lower than the corresponding value of absorbed dose. Therefore, to ensure conservatism and compliance with OCAS-IG-001 (NIOSH 2006), and to avoid underestimation, 1 R of *exposure* was taken to be equal to

1 rad of absorbed dose and to 1 rad (10 mGy) of kerma (1 R = 1 rad = 1 rem has been used in other occupational medical TBDs) [8].

Conversion of *exposure* expressed as ESE was made in accordance with conversion coefficients published in Tables A2 through A8 of ICRP Publication 34 (ICRP 1982). These tables provide average absorbed organ doses for specific selected medical radiographic procedures related to an entrance air kerma without backscatter of 1 Gy for various beam qualities 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 the IREP but not specifically identified in ICRP Publication 34 (ICRP 1982), use of the dose conversion coefficient for the organ in ICRP Publication 34 (ICRP 1982) that is anatomically the closest is a reasonable and simple first-order approach that would generally be favorable to the claimant or neutral [9]. For example, the factor for lung would be applied to all other organs in the thoracic cavity (thymus, esophagus, liver, gall bladder, spleen, and stomach). Because an appreciable fraction of the skeleton, in particular the trabecular bone (which has a large surface-to-volume ratio) and the sternum (which is a primary location of red marrow in the adult), lies within the trunk, the factor for lung would also apply to bone surfaces. For organs in the abdomen (i.e., urinary bladder and colon/rectum), the dose conversion coefficient for ovaries would apply. For the eye and brain, the analogous organ is the thyroid. Table 3-2 lists the analogues for IREP organs not included in ICRP Publication 34. [Figure 3-1 of (ORAUT 2005) shows an organ diagram of the human torso].

Table 3-2. Analogues for IREP organs not in ICRP Publication 34 (ICRP 1982).

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

Because, as discussed above, 1 R was taken to be 10 mGy of kerma, conversion could be made easily if the beam quality was known. Measured beam quality data were not found. However, the applied kilovoltage and filtration were known, 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 (milliampere-seconds), for conservatism, the upper limit on the likely beam quality was calculated and rounded upward to match the closest value in the tables in ICRP Publication 34 (ICRP 1982). For the period before 1957, beam quality expressed as HVL was conservatively estimated to be 2.5 mm Al. After 1957, the estimated HVL was 3.0 mm Al. These values are somewhat higher than the HVL values that would be derived from Table A16 of Publication 34 and, therefore, are favorable to the claimant. The ESE was measured after January 1, 1957, to the present and this *exposure* used ICRP Publication 34 (ICRP 1982) DCFs from Tables A2. through A8 [10].

Table 3-3 lists the frequency of occupationally-required PA and LAT chest X-ray procedures for entrance (preemployment), exit (on leaving), and biennial (periodic) physical examinations from NTS information (Kathren and Shockley 2003). In the early years at the site, periodic X-ray examinations were provided on an annual basis for workers who were required to wear respiratory protection, on employment, and on a 2-year frequency after that. In the early years, individuals in at-risk groups could have received medical examinations including X-rays at various, perhaps even more frequent, intervals. Such workers can be identified from specific medical records. Other employees neither working with radiation nor required to wear respiratory protection could have had X-rays on a 2-year frequency. The X-rays could have been both PA and LAT exposures for most workers when medical examinations were required.

Table 3-3. Frequency of PA and LAT chest X-rays at NTS.[a]

Period	Frequency	Comment
1951–1/1/1957[d]	Entrance[b,f]	All employees
	Exit[b]	All employees
	Biennial[c,f]	For workers respirator qualified[e]
1/1/1957–Present[d]	Entrance[b]	All employees[g]
	Exit[b]	All employees[g]
	Biennial	For workers respirator qualified[e]

a. Source: Kathren and Shockley (2003). Frequency data provided from NTS X-ray records (DeMarre 2002–2003).
b. Entrance and exit X-rays were provided from 1951 to January 1, 1957. These X-rays were not required after 1980 unless personnel were in a job class that required an X-ray.
c. Older workers above age 45 might have been required to have X-ray examinations. Check worker file to verify before adding dose automatically.
d. Do not automatically add the LAT chest dose to the overall worker dose unless there is a record of the examination in the workers file [11].
e. Includes pulmonary function to determine lung function (capacity). Executive physical required this test if respiratory qualified.
f. Private contractors might have performed X-ray examinations off the site until the mid-1960s.
g. Check workers personal file; workers normally did not have LAT X-ray examinations, and PA examinations might have been optional.

3.3.1 Doses from Posterior-Anterior Chest Radiography

Table 3-4 summarizes the salient data for the 14- by 17-in. PA chest radiography. As indicated in the table, PA chest radiography was the most widely used screening procedure. Dates of measurement refer to the dates of measurement or estimate of machine output for the procedure specified. Generally, there is a decreasing trend of ESE with time, which is wholly consistent with national experience (Gray 1996). For conservatism in reconstructing doses and in accordance with the guidance in OCAS-IG-001 (NIOSH 2006), the ESE should be assumed to have been constant from the time of the measurement until the time of the next measurement [12]. Therefore, referring to Table 3-4, PA radiographs taken from 1951 to January 1, 1957 show an ESE of 125 mrem that was derived from BRH (1970), Gray (1996), and Geiger et al. (1960), and radiographs after 1957 show the measured ESE as 40 mrem (Kathren and Shockley 2003).

As discussed in Section 3.2.4, this analysis includes the favorable to claimant assumption that minimal collimation occurred before January 1, 1957. Therefore, for procedures performed before January 1, 1957, substitute DCFs values were used (Table 3-5). The substitute DCFs were used to estimate the organ doses listed in Table 3-6 (which also lists those DCFs).

Table 3-4. Beam parameters for 14- by 17-in. PA chest radiography.[a]

Date measured	1951 to 1/1/1957	1/1/1957 to Present
Procedure	Chest PA 14"×17"	Chest PA 14"×17"
Machine type	Standard X-ray Model # EC-200	Unknown
Machine settings	72 kVp	Unknown
Current	200 mA	Unknown
Exposure time	1/20 s	Unknown

Exposure	10 mAs	Unknown
Added filter	2.0 mm Al	2.5 mm Al
HVL	2.5 mm Al	3.0 mm Al
SID	72 in.	72 in.
ESE	125 mR from Gray (1996)[b]	40 mR from film badge readings[c]

a. Sources: BRH (1970), Gray (1996), Geiger et al. (1960), Kathren and Shockley (2003), and DeMarre (2002–2003).
b. This value determined using information derived from Gray (1996) and Kathren and Shockley (2003).
c. NTS Medical X-Ray equipment Geiger et al. (1960) and film badge readings from Kathren and Shockley (2003).

Table 3-5. Substitute DCFs for PA and LAT chest projections assuming a minimally collimated beam.

Organ of interest	Substitute DCFs by organ and projection
Thyroid	AP cervical spine corrected for depth by a factor of 0.2 [NCRP Report 102 (NRCP 1997, Table B.8, p. 103)] LAT cervical spine
Eye and brain	PA and LAT skull, or PA chest, whichever is larger
Ovaries and analogues, testes, and uterus	PA and LAT abdomen

Organ Dose Calculation Methods – Posterior–Anterior Chest Films

The organ doses for PA chest films were calculated using the exposure expressed as ESE multiplied by conversion coefficients in Tables A-2 through A-8 of ICRP Publication 34 (ICRP 1982). Table 3-6 provides the organ dose information for each period that PA chest X-rays were performed on NTS workers. Because absorbed organ dose for PA chest radiographs for a given exposure and filtration will increase as a function of the HVL, two different values for HVL were used for dose determination. The HVLs were set at a reasonable maximum to ensure adequate doses were calculated. For the period before 1957, the estimated beam quality expressed as HVL was 2.5 mm Al; after 1957, 3.0 mm Al was used (see above for details).

The following are the methods used to calculate the dose in gray from Table 3-6 from 1951 to the present. It is important to note that the PA ESE of 125 mR assumed for 1951 to January 1, 1957, was derived using data from Geiger et al. (1960), BRH (1970), and Gray (1996) for dose calculation based on experience and references from the early 1940s as shown below:

1951 to 1/1/57 — 14- by 17-in. PA chest X-ray with 2.5-mm Al filter and an estimated ESE of 125 mR (0.00125 Gy) (Gray 1996). This value is used with DCF values from Table 3-6 to estimate organ doses from PA chest X-rays.

1/1/1957 to 3/31/2004 — 14- by 17-in. PA chest X-ray with 3.0-mm Al filter and a measured ESE of 40 mR (0.0004 Gy) (Kathren and Shockley 2003). This value is used with DCFs from ICRP Publication 34 (ICRP 1982), Tables A-2 through A-8, to estimate the doses (mGy per Gy air kerma for a beam quality for 3.0 mm Al).

Table 3-6. Organ doses from PA and LAT chest X-rays at NTS from 1951 to present.

Organ	Chest projection	DCF (mGy per Gy air kerma)[(a)] HVL 2.5 mm Al with minimal collimation	Organ dose for PA ESE= 125 mR; LAT ESE= 315 mR for 1951 to 1/1/1957 (rem)[(b,c)] with minimal collimation	DCF (mGy per Gy air kerma)[(a)] HVL 3.0 mm Al with collimation	Organ dose for PA view ESE= 40 mR; LAT ESE= 100 mR for 1/1/1957 to present (rem)[(b,c)] with collimation
Thyroid	PA	174[d]	2.17E-02	46	1.84E-03
	LAT	137[h]	4.32E-02	133	1.33E-02
Eye/brain	PA	32	4.00E-03	46	1.84E-03
	LAT	137[h]	4.32E-02	133	1.33E-02
Ovaries	PA	168[e]	2.1 E-02	1.8	7.20E-05

	LAT	57[e]	1.8 E-02	0.9	9.00E-05
Liver/gall bladder/spleen	PA	451	5.64E-02	535	2.14E-02
	LAT	220	6.93E-02	267	2.67E-02
Urinary bladder	PA	168[e]	2.1 E-02	1.8	7.20E-05
	LAT	57[e]	1.8 E-02	0.9	9.00E-05
Colon rectum	PA	168[e]	2.1 E-02	1.8	7.20E-05
	LAT	57[e]	1.8 E-02	0.9	9.00E-05
Testes	PA	9.1[e]	1.14 E-03	0.01	4.00E-07
	LAT	3.3[e]	1.04 E-03	0.1	1.00E-05
Lungs (male)	PA	419	5.24E-02	496	1.98E-02
	LAT	193	6.08E-02	236	2.36E-02
Lungs (female)	PA	451	5.64E-02	535	2.14E-02
	LAT	220	6.93E-02	267	2.67E-02
Thymus	PA	451	5.64E-02	535	2.14E-02
	LAT	220	6.93E-02	267	2.67E-02
Esophagus	PA	451	5.64E-02	535	2.14E-02
	LAT	220	6.93E-02	267	2.67E-02
Stomach	PA	451	5.64E-02	535	2.14E-02
	LAT	220	6.93E-02	267	2.67E-02
Bone surfaces	PA	451	5.64E-02	535	2.14E-02
	LAT	220	6.93E-02	267	2.67E-02
Remainder	PA	451	5.64E-02	535	2.14E-02
	LAT	220	6.93E-02	267	2.67E-02
Breast	PA	49	6.13E-03	69	2.76E-03
	LAT	255	8.03E-02	287	2.87E-02
Uterus (embryo)	PA	149	1.86 E-02	2.3	9.20E-05
	LAT	43	1.35 E-02	0.9	9.00E-05
Bone marrow (male)	PA	92	1.15E-02	117	4.68E-03
	LAT	37	1.17E-02	48	4.80E-03
Bone marrow (female)	PA	86	1.08E-02	112	4.48E-03
	LAT	29	9.14E-03	38	3.80E-03
Skin	PA	1.35 × 125 mR	1.69E-01[f]	1.4 × 40 mR	5.60E-02[g]
	LAT	1.35 × 315 mR	4.25E-01[f]	1.4 × 100 mR	1.40E-01[g]

a. DCFs from Tables A.2 through A.8 of ICRP 34 (ICRP 1982).
b. Source-to-image distance (SID) = 183 cm.
c. Image Receptor Size (cm) 35.6 x 43.2.
d. DCF for AP cervical spine corrected for depth by 0.2.
e. Substitute DCFs because of assumed poorly collimated beam.
f. Calculated using backscatter factor of 1.35 for HVL of 2.5 mm Al from NCRP Report 102 (NCRP 1997, Table B.8).
g. Calculated using backscatter factor of 1.40 for HVL of 4.0 mm Al from NCRP Report 102 (NCRP 1997, Table B.8).
h. DCF values are for LAT skull, used with minimal collimation for 1951 to 1957, as this results in doses favorable to the claimant.

3.3.2 Lateral 14- by 17-in. Chest Radiography

Table 3-3 summarizes the period, frequency, and applicability for PA and LAT chest X-rays at NTS. Table 3-6 gives the information on ESE and organ doses for the LAT 14- by 17-in. chest projection. Although the LAT 14- by 17-in. chest projection was probably incorporated in the pre- and continuing employment physical examinations at NTS, LAT chest examinations were not always required on a regularly scheduled basis [13]. The dose to most organs from a LAT 14- by 17-in. chest radiograph is significantly greater than that from the more common 14- by 17-in. PA projection. All other factors notwithstanding, the ESE must of necessity be increased because of the greater body thickness presented laterally in comparison to PA. This means that the body will be closer to the X-ray tube and the exposure will increase due to the increased body thickness, which will further increase the ESE (Sante 1946, Sante 1954).

Few measurement data are available for LAT 14- by 17-in. chest projection at NTS [14]. Data by Kirklin et al. (1969) indicate that the ESE from a LAT radiograph was 1.94 times (approximately twice) the ESE from a PA chest radiograph. Depending on the degree of measurement error, this value could be slightly greater or smaller. Because other measurement data suggest that the ratio of ESE from LAT to PA chest radiographs could have been somewhat greater (Cardarelli et al. 2002; Rising and Soldat 1959; Stanford and Vance 1955), and to ensure that dose from this source was not underestimated, a moderately conservative factor of 2.5 was assumed for the ratio of ESE from LAT to PA chest projection for organ dose calculations (i.e., PA ESE times 2.5 was used as LAT ESE).

Organ Dose Calculation Methods – Lateral Chest Projection
The organ doses for LAT chest projection were calculated using the exposure expressed as ESE multiplied by conversion coefficients in Tables A-2 through A-8 of ICRP Publication 34 (ICRP 1982). Several of the above references support the use of a factor of 2.5 times the PA chest ESE for the LAT chest ESE, and this factor was used to determine doses for LAT chest radiographs for NTS workers for 1951 to the present. Because absorbed organ dose for LAT chest radiographs increases as a function of the HVL, which in turn is a function of the Al filter thickness used, two HVLs were used for dose determination. For the period before January 1, 1957, the estimated beam quality expressed as HVL is 2.5 mm Al; after January 1, 1957, the estimated HVL is 3.0 mm Al.

The following are the methods used to calculate the organ dose in gray from ESEs and DCFs listed in Table 3-6 (1951 to the present). The ESE for the LAT projection used for 1951 to January 1,1957, is 2.5 times the assumed PA ESE of 125 mR, or 315 mR (rounded up) for the LAT chest radiograph.

1951 to 1/1/57	14- by 17-in. LAT chest X-ray with 2.5-mm Al filter and an assumed ESE of 315 mR (0.00315 Gy). This value is used with DCF values from Table 3-6 to determine organ dose values for the listed organs in ICRP Publication 34 (ICRP 1982).
1/1/57 to 3/31/2004	14- by 17-in. LAT chest X-ray with 3-mm Al filter and a calculated ESE of 100 mR (0.001 Gy) (2.5 multiplied by 40 mR measured ESE). This value is used with DCF values from Tables A-2 through A-8 from ICRP Publication 34 (ICRP 1982).

3.4 UNCERTAINTY ANALYSIS FOR RADIOGRAPHY DOSES

Error (deviation from the correct, true, or conventionally accepted value of a quantity) and *uncertainty* (defined in terms of the potential range of a stated, measured, assumed, or otherwise determined value of a quantity) provide an indication of the confidence of the dose estimates. Error implies knowledge of what the correct or actual value is, which is of course not known. Therefore, the more appropriate term is *uncertainty*, which is expressed in terms of a confidence level (e.g., a 99% confidence level indicates that the correct or true value, although not actually known, has a 99% probability of falling within the range cited) and includes both precision or reproducibility of the measurement and accuracy, or how close the measurement or estimate of dose comes to the actual or correct value [15].

In theory, a large number of factors can introduce uncertainties or affect the X-ray machine output intensity and dose to the worker. However, because X-ray doses at NTS were derived largely from actual beam intensity measurements, in practice, only five factors can be reasonably considered to have an impact on dose uncertainty:

1. Measurement error [16]
2. Variation in applied kilovoltage
3. Variation in beam current
4. Variation in exposure time
5. Distance from the worker to the source of the X-rays (SSD)

The influence of such other factors as use of screens, grids, reciprocity failure, film speed, and development issues, while potentially variable, would not affect the beam output intensity.

Medical X-ray doses at NTS were largely derived from actual measurement of X-ray machine output with R-meters or similar ionization chamber devices (Kathren and Shockley 2003). If properly calibrated and used, these typically and historically have had an uncertainty of ±2% for photon energies below 400 keV (Kathren and Larson 1969). Although more recent versions of these instruments might provide a somewhat smaller uncertainty, perhaps on the order of ±1% (NBS 1985, 1988), for conservatism, the uncertainty range of ±2% should be applied to measurements of X-ray intensity at NTS [17].

For a given set of machine settings and parameters, X-ray output is theoretically constant and unvarying. However, this is not true in practice, although output is essentially constant unless focal spot loading occurs, as could be the case when the power rating of the machine is exceeded. It is unlikely that power ratings were ever exceeded because such an event would be difficult to achieve in practice and could result in damage to the X-ray tube. However, even with the use of constant-voltage transformers to control line voltages, slight variations can occur in line voltage input or other internal voltages, which in turn can alter the applied kilovoltage of the output beam. In general, for a given applied kilovoltage setting, variation 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 kilovoltage; this translates to an uncertainty of approximately ±8.6% in relation to output beam intensity in the 80- to 100-kVp range used for diagnostic chest radiographs at NTS. For conservatism, this is rounded up to ±9% [18].

Similarly, slight variations in tube current are normal; as a tube ages or heats up from use, current can change and typically drops. With all other factors constant, beam intensity is reduced in direct proportion to the change in tube current. Typically, the reduction in beam output from current variation is not more than a few percent under normal operating conditions; large decreases are readily detectable and manifest themselves as underexposed radiographs, which results in maintenance on the machine to restore the output or, as a temporary measure, an increase in the current or applied kilovoltage to provide the necessary intensity for proper radiography. There is no evidence to suggest that such temporary measures were ever necessary or used at NTS. For a given applied kilovoltage setting, the output of the beam is a function of the tube current, which is measured by a milliammeter that measures the average tube current. The measurement is subject to uncertainties; there can 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 conservatively taken to be ±5% [19].

Another parameter with the 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, only six pulses result. A small error in the timer that resulted in a change of only 1 pulse would correspondingly affect the output by ±17%; for an exposure time of 1/30 of a second, the change in output corresponding to a deviation of 1 pulse would be ±25%. Early mechanical timers were notoriously inaccurate; accuracy improved significantly with the introduction of electronic timers. Measurements of reproducibility made in the late 1980s and beyond by the State of Washington for the machines at Hanford suggest that the timers, and indeed the entire X-ray output, were fairly constant (WDOH 1990–1999). However, for conservatism, the assumed uncertainty in beam output attributable to timers at NTS has an upper limit of ±25% [20].

The final factor likely to affect worker dose relates to distance 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 body thickness 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, this indicates an uncertainty of ±10% from this source [21].

There are two approaches to determine the combined uncertainty from the five potential sources. The first, and most conservative in that it gives the greatest range, would be to assume that the uncertainties are additive, which would give an uncertainty range of ±51% (2 + 9 +5 + 25 + 10). However, a more reasonable approach would be to assume that the uncertainties are in fact random and to compute the statistical root mean square (RMS) value. The RMS value is simply the square root of the sum of the squares, and it computes as ±28.9%. Rounding this up to ±30% would seem to provide an adequate and suitably conservative indication of uncertainty. Therefore, for an individual ESE or derived organ dose, an uncertainty of ±30% can be assumed. For further conservatism, it would be appropriate to assume that errors are all positive, and only +30% should be used [22].

3.5 ATTRIBUTIONS AND ANNOTATIONS

Where appropriate in the preceding text, bracketed callouts have been inserted to indicate information, conclusions, and recommendations to assist in the process of worker dose reconstruction. These callouts are listed in this section with information that identifies the source and justification for each item. Conventional references are provided in the next section that link data, quotations, and other information to documents available for review on the Oak Ridge Associated Universities (ORAU) Team servers.

Vernon E. Shockley served as one of the initial Subject Experts for this document. Mr. Shockley was previously employed at NTS, and his work involved management, direction, or implementation of radiation protection and/or health physics program policies, procedures, or practices related to atomic weapons activities at the site. This revision has been overseen by a Document Owner who is fully responsible for the content, including all findings and conclusions. Mr. Shockley continues to serve as a Site Expert for this document because he possesses or is aware of information relevant to reconstruction of radiation doses experienced by claimants who worked at the site. In all cases where such information or previous studies or writings are included or relied upon by Mr. Shockley, those materials are fully attributed to the source. Mr. Shockley's Disclosure Statement is available at www.oraucoc.org.

[1] Shockley, Vernon E. ORAU Team. Principal Health Physicist. March 2007.
The statement on linearity is based on numerous conversations with Ronald Kathren in relation to his experience in measurement of personnel doses. He has indicated that they have clearly shown linearity.

[2] Shockley, Vernon E.. ORAU Team. Principal Health Physicist. March 2007.
Based on the knowledge, experience, and observations of Ronald Kathren.

[3] Shockley, Vernon E. ORAU Team. Principal Health Physicist. March 2007.
In 2002 and 2003, Martha DeMarre, Document Control Manager, Nuclear Testing Archives, Nevada Test Site (NTS) was contacted by the TBD Subject Expert. She had not and did not

find any information on the use of photofluorography (PFG) at the NTS. Ms. DeMarre had been working in Document Control at the NTS since the early 1960s, and she stated she had seen no indication in the files that NTS used PFG.

[4] Shockley, Vernon E. ORAU Team. Principal Health Physicist. March 2007.
This statement was provided by Ronald Kathren. There was no information found in the records that indicated NTS used a constant potential waveform X-ray machine.

[5] Shockley, Vernon E. ORAU Team. Principal Health Physicist. March 2007.
This statement was provided by Ronald Kathren. There was no information found in the records that indicated NTS used a constant potential waveform X-ray machine.

[6] Shockley, Vernon E. ORAU Team. Principal Health Physicist. March 2007.
DeMarre (2002–2003) indicates that NTS based X-ray doses on measurements of the X-ray beam with NTS film badges, which makes waveform of minor or little significance to the workers.

[7] Shockley, Vernon E. ORAU Team. Principal Health Physicist. March 2007.
This statement is based on conversations with Ronald Kathren and his personal knowledge of this subject. No information has been found for the NTS that indicates otherwise.

[8] Shockley, Vernon E. ORAU Team. Principal Health Physicist. March 2007.
This statement was made by Ron Kathren because this is required in 10 C.F.R. pt. 20 by the U.S. Nuclear Regulatory Commission.

[9] Kathren, Ronald L., and Shockley, Vernon E. Kathren Group and ORAU Team. Consultant and Principal Health Physicist. June 2004.
In conversations with Timothy Taulbee, he indicated that ORAUT-OTIB-0006 (ORAUT 2005) provided data to support the use of IREP code organs anatomically closest to the organ of interest. This is a reasonable method of determination.

[10] Shockley, Vernon E. ORAU Team. Principal Health Physicist. March 2007.
Discussions (e-mail and verbal) between Timothy Taulbee and Ronald Kathren resulted in the decision to use the beam quality of 2.5 mm Al HVL for years before 1957 at NTS. The DCFs based on this beam quality were conservative and favorable to claimants. After 1957 the beam quality was determined using an HVL of 3.0 mm Al. These DCF values were somewhat higher than the HVL values that would be derived using Table A16 of ICRP Publication 34 (ICRP 1982) and are used because they are favorable to claimants. The ESE was measured after January 1, 1957, to the present using ICRP Publication 34 (ICRP 1982) DCFs from Tables A2 through A8.

[11] Kathren, Ronald L., and Shockley, Vernon E. Kathren Group and ORAU Team. Consultant and Principal Health Physicist. March 2007.
Discussion and e-mail correspondence with Martha DeMarre indicated that some LAT chest X-ray exams were provided, but not on a routine basis.

[12] Shockley, Vernon E. ORAU Team. Principal Health Physicist. March 2007.
Based on discussion with Ronald Kathren about ESE measurement being constant from the time of one measurement to the next. This assumption ensures ESE doses are consistent and that the resulting organ doses remain consistent with OCAS-IG-001 guidance (NIOSH 2006).

[13] Kathren, Ronald L., and Shockley, Vernon E. Kathren Group and ORAU Team. Consultant and Principal Health Physicist. March 2007.
During discussions and e-mail correspondence with Martha DeMarre, she stated that the records show that PA chest X-rays were usually required for pre- and continuing physical exams, but LAT X-ray exams were not.

[14] Kathren, Ronald L., and Shockley, Vernon E. Kathren Group and ORAU Team. Consultant and Principal Health Physicist. March 2007.
Discussion and e-mail correspondence with Martha DeMarre indicated that some LAT chest X-ray exams were provided, but not on a routine basis.

[15] Kathren, Ronald L., and Shockley, Vernon E. Kathren Group and ORAU Team. Consultant and Principal Health Physicist. March 2007.
The information in the referenced documents for NTS is adequate to calculate doses that were received from occupationally required X-rays. There are uncertainties about how the measurements methods were performed to determine the total filtration values during this time. Therefore, an approach that is favorable to the claimants was used for this TBD. This approach included the calculation of the entrance kerma based on information in NCRP (1997, Table B.3) for the given kVp and a distance of 183 cm that was then corrected based on an assumed chest size of 24 cm with 5 cm between the chest and film using the inverse square law for point sources. This value was then corrected based on the provided current and exposure times. NCRP (1997, Table B.3) provides information based on a total filtration of 2.5 mm Al. This was adjusted to account for the stated 1.5 mm Al based on the following formula where t is the thickness of aluminum in millimeters and I and I_o are the beam intensities with and without the filter, respectively:

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

Given the uncertainty with measurements to determine the total filtration values, an assumption was made to apply DCFs based on 2.5-mm Al HVL in ICRP (1982), which is favorable to the claimants.

[16] Kathren, Ronald L., and Shockley, Vernon E. Kathren Group and ORAU Team. Consultant and Principal Health Physicist. March 2007.
The information in the referenced documents for NTS is adequate to calculate doses that were received from occupationally required X-rays. There are uncertainties about how the measurements methods were performed to determine the total filtration values during this time. Therefore, an approach that is favorable to the claimants was used for this TBD. This approach included the calculation of the entrance kerma based on information in NCRP (1997, Table B.3) for the given kVp and a distance of 183 cm that was then corrected based on an assumed chest size of 24 cm with 5 cm between the chest and film using the inverse square law for point sources. This value was then corrected based on the provided current and exposure times. NCRP (1997, Table B.3) provides information based on a total filtration of 2.5 mm Al. This was adjusted to account for the stated 1.5 mm Al based on the following formula where t is the thickness of aluminum in millimeters and I and I_o are the beam intensities with and without the filter, respectively:

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

Given the uncertainty with measurements to determine the total filtration values, an assumption was made to apply DCFs based on 2.5-mm Al HVL in ICRP (1982), which is favorable to the claimants.

[17] Shockley, Vernon E. Dade Moeller & Associates. Principal Health Physicist. March 2007. Discussions with Ronald Kathren indicated that the uncertainty might have become smaller, but the uncertainty remained in the TBD at ±5 % for conservatism and the difference is negligible.

[18] Kathren, Ronald L., and Shockley, Vernon E. Kathren Group and ORAU Team. Consultant and Principal Health Physicist. March 2007.
The information in the referenced documents for NTS is adequate to calculate doses that were received from occupationally required X-rays. There are uncertainties about how the measurements methods were performed to determine the total filtration values during this time. Therefore, an approach that is favorable to the claimants was used for this TBD. This approach included the calculation of the entrance kerma based on information in NCRP (1997, Table B.3) for the given kVp and a distance of 183 cm that was then corrected based on an assumed chest size of 24 cm with 5 cm between the chest and film using the inverse square law for point sources. This value was then corrected based on the provided current and exposure times. NCRP (1997, Table B.3) provides information based on a total filtration of 2.5 mm Al. This was adjusted to account for the stated 1.5 mm Al based on the following formula where t is the thickness of aluminum in millimeters and I and I_o are the beam intensities with and without the filter, respectively:

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

Given the uncertainty with measurements to determine the total filtration values, an assumption was made to apply DCFs based on 2.5-mm Al HVL in ICRP (1982), which is favorable to the claimants.

[19] Shockley, Vernon E. Dade Moeller & Associates. Principal Health Physicist. March 2007. Discussions with Ronald Kathren indicated that the uncertainty might have become smaller but the uncertainty remained in the TBD at ±5 % for conservatism and the difference is negligible.

[20] Shockley, Vernon E. Dade Moeller & Associates. Principal Health Physicist. March 2007. Discussions with Ronald Kathren indicated that the uncertainty associated with timers might have become smaller but the uncertainty remained at ±25 % for conservatism and the difference is negligible because this is an upper limit.

[21] Kathren, Ronald L., and Shockley, Vernon E. Kathren Group and ORAU Team. Consultant and Principal Health Physicist. March 2007.
The information in the referenced documents for NTS is adequate to calculate doses that were received from occupationally required X-rays. There are uncertainties about how the measurements methods were performed to determine the total filtration values during this time. Therefore, an approach that is favorable to the claimants was used for this TBD. This approach included the calculation of the entrance kerma based on information in NCRP (1997, Table B.3) for the given kVp and a distance of 183 cm that was then corrected based on an assumed chest size of 24 cm with 5 cm between the chest and film using the inverse square law for point sources. This value was then corrected based on the provided current and exposure times. NCRP (1997, Table B.3) provides information based on a total filtration of 2.5 mm Al. This was adjusted to account for the stated 1.5 mm Al based on the following

formula where t is the thickness of aluminum in millimeters and I and I_o are the beam intensities with and without the filter, respectively:

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

Given the uncertainty with measurements to determine the total filtration values, an assumption was made to apply DCFs based on 2.5-mm Al HVL in ICRP (1982), which is favorable to the claimants.

[22] Shockley, Vernon E. Dade Moeller & Associates. Principal Health Physicist. March 2007. In discussions with Ronald Kathren, he indicated that the added uncertainties of ±51% do not take into consideration random uncertainties. Using the RMS values provides a more statistically accurate value of ±28.9%. Rounding this up to ±30% and assuming that +30% should be used is favorable to the claimant for dose reconstruction.

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GLOSSARY

entrance skin exposure (ESE)
The exposure at the point where the X-ray beam enters the skin.

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

filtration
Material in the useful beam, which preferentially absorbs photons from the beam.

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

fluence
A measure of the quantity of X-rays in a beam in diagnostic radiology, either particle fluence (the number of photons entering a sphere of unit cross-sectional area) or energy fluence (the sum of the energies of the photons passing through a unit area).

gray (Gy)
The special name for the SI unit of absorbed dose, kerma, and specific energy imparted equal to one (1) joule per kilogram (J/kg). (1 Gy = 1 J/kg = 100 rad).

grid
A series of lead strips used to improve the quality of radiographic images by removing scattered X-rays.

half-value layer (HVL)
Thickness of a specified substance which, when introduced into the path of a given beam of radiation, reduces the kerma rate by one-half (usually specified in mm Al).

Interactive RadioEpidemiological Program (IREP)
A computer software program that uses information on the dose-response relationship and specific factors such as a claimant's radiation exposure, gender, age at diagnosis, and age at exposure to calculate the probability of causation for a given pattern and level of radiation exposure.

International Commission on Radiological Protection (ICRP)
An independent international scientific body, established to advance for the public benefit the science of radiological protection, in particular by providing recommendations and guidance on all aspects of protection against ionizing radiation.

inverse square law
The mathematical relationship between the exposure rate from a point source of radiation and the distance from the source.

kerma
The sum of the initial kinetic energies of all the charged ionizing particles liberated by uncharged ionizing particles per unit mass of a specified material.

kiloelectron-volt (keV)
The energy equal to that acquired by a particle with one electron charge in passing through a potential difference of 1000 volts.

milliammeter
An instrument for measuring electric current in milliamperes.

National Council on Radiation Protection and Measurements (NCRP)
A nongovernmental, public service organization that formulates and disseminates information, guidance, and recommendations on radiation protection and measurements.

organ dose
The dose to a given organ from an X-ray procedure.

photofluorography
An obsolete radiographic technique in which the image produced on a fluorescent screen by X-rays was photographed.

photon
A quantum of electromagnetic radiation.

posterior–anterior (PA)
A radiographic position in which the X-ray beam passes from posterior to the anterior side of the body.

preemployment X-ray
A radiograph, usually a chest X-ray, taken before a worker is hired or assigned to a specific job used to screen for active disease.

probability of causation (POC)
The probability or likelihood that a cancer was caused by occupational exposure to ionizing radiation.

pulmonary
Relating to, functioning like, or associated with the lungs.

radiograph

A photographic negative or image made with X-rays.

root mean square
The square root of the arithmetic mean of the squares of a set of numbers.

screens
Fluorescent material in X-ray film cassettes that absorbs the X-rays and converts them into light that exposes the X-ray film.

source-to-image distance (SID)
The distance measured along the central ray from the center of the front of the surface of the source (focal spot) to the surface of the image detector.

source-to-skin distance (SSD)
The distance measured along the central ray from the center of the front of the surface of the source (focal spot) to the surface of the irradiated object or the patient.

technique factors
The variables in machine setting [i.e., the peak voltage (kVp), current (mA), and time (s)] that are used for exposing a radiograph.

termination X-ray
An X-ray, usually a chest X-ray, that is taken when the employee is separated from the company.

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

variable
A quantity that may assume any one of a set of values.

X-ray
Ionizing electromagnetic radiation originating outside the nucleus; also, a radiograph or photographic negative or image made with X-rays.

X-ray tube
An evacuated electronic tube in which X-rays are generated when electrons are accelerated by an applied voltage and strike an anode or target.