ORAU Team **NIOSH Dose Reconstruction Project** Technical Basis Document for the Nevada Test Site – Occupational Medical Dose	Document Number: ORAUT-TKBS-0008-3 Effective Date: 06/09/2004 Revision No.: 00 Controlled Copy No.: ________ Page 1 of 22
Subject Experts: Vern Shockley, Ron Kathren Document Owner: Approval: Signature on File Date: 06/08/2004 Eugene Rollins, TBD Team Leader Approval: Signature on File Date: 06/08/2004 Judson L. Kenoyer, Task 3 Manager Concurrence: Signature on File Date: 06/08/2004 Richard E. Toohey, Project Director Approval: Signature on File Date: 06/09/2004 James W. Neton, OCAS Health Science Administrator	Supersedes: None

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RECORD OF ISSUE/REVISIONS

ISSUE AUTHORIZATION DATE	EFFECTIVE DATE	REV. NO.	DESCRIPTION
Draft	10/16/2003	00-A	New technical basis document for the Nevada Test Site – Occupational Medical Dose. Initiated by Eugene Rollins.
Draft	04/20/2004	00-B	Incorporates internal review and NIOSH comments. Initiated by Eugene Rollins.
Draft	05/27/2004	00-C	Incorporates NIOSH comments. Initiated by Eugene Rollins.
06/09/2004	06/09/2004	00	First approved issue. Initiated by Eugene Rollins.

ACRONYMS AND ABBREVIATIONS

Al	aluminum
cm	centimeter
DF	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
IREP	Interactive RadioEpidemiological Program
kVp	peak kilovoltage, applied kilovoltage
LAT	lateral
mA	milliampere
mAs	milliampere-second
mm	millimeter
NCRP	National Council on Radiation Protection and Measurement
NIOSH	National Institute for Occupational Safety and Health
NTS	Nevada Test Site
PA	posterior-anterior
R	roentgen
RMS	root mean square
sec	second
SID	source-to-image distance
SSD	source-to-skin distance
TBD	technical basis document

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 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 facility” as defined in the Energy Employee Occupational Illness Compensation Program Act of 2000 (42 U.S.C. § 7384l (5) and (12)).”

Diagnostic x-ray procedures were a contributor to the occupational radiation exposure of Nevada Test Site (NTS) workers. In general, the dose from these exposures was not measured or considered or included as part of the overall occupational exposure of the employee, although it clearly was related. Under the EEOICPA program, diagnostic medical x-rays administered in conjunction with routine or special physical examinations required for employment were recognized as a valid source of occupational exposure. Unlike occupational exposures incurred during normal work processes, individual diagnostic medical x-ray exposures were not monitored, necessitating reconstruction of doses acquired in this manner. However, the NTS used a unique practice in which employees received film badges on arrival at the Mercury gate for work. In some instances, workers wore those badges during initial employment physicals, which included routine posterior-anterior (PA) and lateral (LAT) chest x-rays. Examination of these badges provided measured doses for PA and LAT x-rays to workers for this period. This was confirmed by Health Physicists reading archived badges for the period 1957 to the end of testing in September 1992 (DeMarre 2003). This technical basis document (TBD) describes the technical aspects of dose reconstruction from medical x-rays administered prior to employment and periodically thereafter as a condition of employment.

3.2 TECHNICAL FACTORS THAT AFFECT DIAGNOSTIC X-RAY DOSE

A number of factors determine the dose to workers from a diagnostic x-ray procedure. For a standard medical radiographic (i.e., diagnostic) unit with a tungsten target (anode) and focal spot of 1 to 2 mm, these include the basic machine settings used for the exposure, which include the applied kilovoltage of the beam (kVp), beam current (mA), time of exposure (sec), distance (cm), 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 three basic machine parameters (applied kilovoltage, current, and time) with assumptions about filtration, collimation, and waveform characteristics. The following sections discuss implications of these factors to worker dose. However, if x-ray exposure or dose measurements are available, as they are for some NTS procedures, dose reconstructions should use such measurements rather than secondary methods such as calculation.

3.2.1 Applied Kilovoltage and Filtration

The energy of the x-ray beam is determined by the applied kilovoltage and the filtration, and is sometimes referred to as beam quality. X-rays, as 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 energy, or applied kilovoltage. Therefore, most x-rays produced are much lower in energy than the applied kilovoltage of the beam, are attenuated by the torso or other portion of the body being radiographed, and never reach the film. These x-rays are of little value in radiography but contribute significantly to worker dose.

To reduce the dose to the worker, filtration in the form of a specified thickness of absorbing material is added to the beam. 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, although the photon fluence 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.

Beam energy is specified in terms of quality, or hardness, which in turn can be in terms of the half-value layer (HVL) in millimeters of aluminum (mm Al). 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 or its true quality because, as the HVL measurement is made, the absorbers act as filters and the beam is further hardened. Thus, the first HVL is always smaller than the second, which in turn is smaller than the third, and so forth. What is commonly, although 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 or port of the tube. In medical diagnostic units, the window is thin, typically equivalent to 0.5 mm Al in attenuation, which provides little beam hardening.

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 Committee for Radiological Units, albeit 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 (NBS1936). 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 use 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. 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[1] 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*[2] (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). Therefore, the approximate intensity reduction afforded by any thickness of Al filtration can be determined by the following exponential equation:

$$I = I_o e^{-0.5t} \qquad (3.2.1\text{-}1)$$

or

$$\ln (I/I_o) = -0.5\ t$$

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 in NIOSH (August 2002).

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 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, and is fully consistent with the guidance in NIOSH (August 2002).

3.2.2 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. Therefore, all 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, flowing from the cathode to the anode. In theory, for a given applied kilovoltage, the number of x-ray photons produced (and therefore the exposure) will be directly proportional to the x-ray tube current. This is and has been true for most

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1. 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.
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. A brief discussion of exposure in both the general and special sense 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.

medical radiography units over their design tube current range. 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) to assume linearity of exposure with tube current for a given applied kilovoltage and filtration.

Exposure time refers to the time 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 proportionately increased to obtain the desired exposure. However, from a dose reconstruction standpoint, 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 might produce uncertainties of perhaps ±20% in the exposure. 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.

3.2.3 Distance

X-ray beam intensity is a function of distance from the target, approximating the inverse square at large distances from the tube. Radiographic chest films were taken at a standard source-to-image distance (SID)[3] 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, 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 attenuation would further reduce or attenuate the number of photons that reached the film.

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 kVp. Therefore, it could be appropriate for an individual dose reconstruction to increase the ESE for a large or stout worker. Based on standard contemporary techniques (Picker 1941; Fuchs 1958; Cahoon 1961) for workers with a chest thickness of 25 to 27 cm, an increase of 50% from the ESE to the average worker should be sufficiently conservative; for still larger workers, a factor of 2 would be appropriate. The average worker's chest size is 22 to 24 cm.

3.2.4 Collimation and Waveform Characteristics

Collimation and waveform characteristics are among the factors that affect dose. X-ray waveforms are of three types: half-wave rectified, which is almost never seen; full-wave rectified, which is typical of medical radiographic units and characteristic of the units used at NTS; 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 s. A full-wave rectified machine produces 120 half-sinusoidal pulses per second, each with a duration of 1/120 s. 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

3. Also known as film-to-focus distance (FFD).

from a full-wave rectified machine. A constant potential machine produces a more or less steady (i.e., unpulsed) output of x-rays and has a somewhat greater (about 10%) beam intensity than a full-wave rectified machine operating at the same parameters.

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

Collimation refers to the size of beam. The early philosophy was to use 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 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 leaves a small unexposed area or penumbra effect at the edges of the radiograph, while a poorly collimated beam produces a radiograph that is exposed over all of its area. Available data, including direct beam measurements, indicate that x-ray beams used at NTS were well collimated (DeMarre 2003). However, this analysis includes the claimant favorable assumption that minimal collimation occurred prior to January 1, 1957. Thus, for ESE values for procedures performed prior to January 1, 1957, DCF values from Table 4.0-1 and the DCFs from Table 5.1-1 “Substitute Dose Conversion Factors” from ORAUT-OTIB-0006 (ORAU 2003) were used to estimate organ doses.

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, 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 briefly mentions these factors, which are tube housing, film type, film speed, development procedure, screens, and grids.

X-ray tubes used for diagnostic radiography are typically enclosed in protective lead or shield 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 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 NTS, had protective tube housings.

The amount of exposure needed for a suitable diagnostic 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. Underdevelopment of films also requires additional exposure to achieve satisfactory radiographic quality. Intensifying screens are used in the cassette to intensify the radiographic effect and thereby increase film speed and reduce worker dose. Grids, specifically the Potter-Bucky diaphragm (known as Bucky), are sometimes used for thick-section radiography but rarely for chest radiography except with large workers.

For convenience and possible application to cases in which the standard NTS protocol was not followed, or for generic use, Table 3-1 lists the effects of various technical factors. However, the parameters discussed in this section are all factored into the technique (i.e., kVp, mA) that is used and, with the exception of rare instances and a virtually complete absence of other data, are not important to dose reconstruction.

3.3 DIAGNOSTIC 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 only two diagnostic medical radiographic procedures were administered in connection with pre-employment or regular post-employment medical examinations:

1. 14” by 17” PA chest films
2. 14” by 17” LAT chest films

Therefore, this analysis evaluated only doses from these two techniques. Other possible radiographic examinations of NTS employees would have been non-occupational in the sense that they were necessitated by illness or injury and were not part of the employee physical examination process. There is no indication in the records that other diagnostic radiographic examinations were administered as part of the occupational medical program, or that radiological treatment for shrinkage of lymphoid tissue was ever performed on NTS workers.

A potential problem common to all procedures relates to the conversion of *exposure* represented by ESE to absorbed organ dose, and 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, which itself is obsolete. Thus, there is much confusion about the definition of exposure and its associated unit, 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.

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. Thus, an exposure to air of 1 R would result in an absorbed dose of somewhat less than 1 rad (1cGy =10 mGy). Nonetheless, 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 R, which was numerically equated as 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 NIOSH (2002), and to avoid underestimation, 1 R of *exposure* was taken to be equal to1 rad of absorbed dose and to 1 rad (10 mGy) of kerma.

Conversion of exposure expressed as ESE was made in accordance with conversion coefficients published in Tables A2 through A9 of ICRP Publication 34 (1982). 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 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 (1982), use of the dose conversion coefficient for the organ in ICRP 34 (1982) that is anatomically the closest is a reasonable and simple first-order approach that would generally be claimant-favorable or neutral. 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/brain, the analogous organ is the thyroid. See Table 3.1-1 “Analogues for IREP Organs not Included in ICRP 34 (1982)” (NIOSH 2003) for details. Please note that Uterus/Embryo are ICRP 34 (1982) listed organs.

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 voltage 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 (mAs), 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 34 (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 ICRP 34 (1982) and, therefore, are claimant-favorable. The ESE dose was measured after January 1, 1957 to the present and this dose used with ICRP 34 (1982) DCFs from Tables A-2 through A-9

Table 3-2 and 3-3 list the frequencies of various occupationally required x-ray procedures for pre-employment (entrance), exit (on leaving), and biennial (routine), from NTS information (DeMarre 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 exams, including x-rays at various, perhaps even more frequent, intervals. Such workers can be identified from specific medical records. Other employees not working with radiation or 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 exams were required.

3.3.1 Doses from Posterior–Anterior Chest Radiography

Table 3-4 summarizes the salient data for the 14 “ by 17 “ PA chest radiography. As indicated in the tables, PA chest radiography was the widely used diagnostic procedure. Dates of measurement refer to the dates of measurement or estimate of machine output for the procedure specified. There is a generally decreasing trend of ESE with time, which is wholly consistent with what has been the experience nationally (Gray 1996). For conservatism in determining or reconstructing doses and in accordance with the guidance in NIOSH (2002), the ESE should be assumed to have been constant from the time of the measurement until the time of the next measurement. Thus, referring to Table 3-4, radiographs taken from 1951 to January 1, 1957, show ESE at 125 mrem, while ESE for radiographs after 1957 show the measured ESE at 40 mrem.

Organ Dose Calculation Methods – Posterior-Anterior (PA) Chest Films
Organ doses for PA chest films were calculated using the exposure expressed as ESE and in accordance with conversion coefficients in Tables A2 through A9 of ICRP 34 (1982). Table 3-4 provides the measured dose information for each period during the PA chest x-rays were given to NTS workers. Because absorbed organ dose for PA chest radiographs for a given exposure (mAs)

and filtration, will increase as a function of the HVL, two different values for HVL were calculated and used for dose determination. The HVLs were set at a reasonable maximum to insure adequate doses were calculated. For the period prior to 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).

Following are methods used to calculate the dose in gray (Gy) from Table 3-4 measured and calculated doses used in the dose determination for each period from 1951 to the present. [Note: The PA ESE assumed for 1951 to January 1, 1957, of 125 mR was derived using data from Geiger (1960), BRH (1970) and Gray (1996) for dose calculation basis and based on experience and references from the early 1940s as shown below]:

1951 to 1/1/57	14” × 17” PA chest x-ray with 2.5-mm Al filter and an estimated (Gray 1996) ESE of 125 mR. Absorbed dose in Gy determined by 125 mR/100 mR per mGy = 1.25 mGy and 1.25 mGy/1000 mGy per 1 Gy = 0.00125 Gy. This value in Gy is used with DCF values from Table 4.0-1 and the DCFs from Table 5.1-1 “Substitute Dose Conversion Factors” from ORAUT-OTIB-0006 (ORAU 2003) to estimate organ dose conversion factors (mGy per Gy air kerma for a beam quality for 2.5 mm Al HVL). These (DFs) were used to determine dose values for the listed organs in ICRP 34 (1982).
1/1/1957 to 3/31/2004	14” × 17” PA chest x-ray with 3.0mm Al filter and a measured ESE of 40 mR (DeMarre 2003). Absorbed dose in Gy determined by 40 mR/100mGy per mR = 0.40 mGy and 0.40 mGy/1000mGy per 1 Gy = 0.00040 Gy. This value in Gy is used with estimated dose conversion factors from ICRP 34 (1982) Tables A-2 through A-9 (mGy per Gy air kerma for a beam quality for 3.0 mm Al HVL). These DCFs were used to determine organ dose values for the listed organs in ICRP 34 (1982).

3.3.2 Lateral (LAT) 14” by 17” Chest Radiography

Tables 3.3 and 3.3 continued, summarizes period, frequency, applicability, ESE, and organ doses for the lateral 14” by 17” chest radiography. Although lateral 14” by 17” chest radiography was probably incorporated in the pre- and continuing employment physical examinations at NTS, lateral chest exams were not always required on a regularly scheduled basis. The dose from a lateral 14” by 17” chest radiograph is significantly greater than that from the more common 14” by 17” PA chest radiography procedure. 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 mAs will increase due to the increased body mass, which will further increase the ESE. Few measurement data are available for lateral 14” by 17” chest radiography at NTS. Data by Kirklin et al. (1969) indicate that the ESE from a lateral radiograph was 1.94 times the ESE from a PA chest radiograph, or 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 measured data suggest that the ratio of ESE from lateral to PA chest radiographs could have been somewhat greater (Cardarelli et al. 2002; Rising and Soldat 1959; Stanford and Vance 1955), 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 lateral to PA chest radiography for organ dose calculations, i.e. PA ESE times 2.5 was used as Lat ESE.

Organ Dose Calculation Methods – Lateral Chest Radiography

The organ doses for lateral (LAT) chest radiography were calculated using the exposure expressed as ESE and were in accordance with conversion coefficients in Tables A2 through A9 of ICRP (1982). Several of the above references support the use of a factor of 2.5 times the PA chest radiography ESE dose for the lateral chest radiography dose and this factor was used to determine doses for lateral chest radiography for NTS workers for 1951 to the present. Because absorbed organ dose for lateral chest radiographs increases as a function of the HVL of the Al filter used, two HVLs were calculated and used for dose determination. For the period prior to 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.

Following are methods used to calculate the dose in Gy from doses listed in Tables 3-3 and 3.3 continued, that are used in the dose determination for each period from 1951 to the present. The ESE for the lateral view used for 1951 to January 1, 1957, is 2.5 times the 125 mR PA assumed ESE, or 315 (rounded up) mR for the lateral chest radiograph.

1951 to 1/1/57	14” × 17” Lat chest x-ray with 2.5-mm Al filter and an assumed ESE of 315 mR. Absorbed dose in Gy determined by 315 mR/100mR per mGy = 3.15 mGy and 3.15 mGy/1,000 mGy per 1 Gy = 0.00315 Gy. This value in Gy is used with DCF values from Table 4.0-1 and the DCFs from Table 5.1-1 “Substitute Dose Conversion Factors” from ORAUT-OTIB-0006 (ORAU 2003) to estimate organ dose conversion factors (mGy per Gy air kerma for a beam quality for 2.5 mm Al HVL). These DCFs were used to determine organ dose values for the listed organs in ICRP 34 (1982).
1/1/57 to 3/31/2004	14” × 17” LAT chest x-ray with 3.0-mm Al filter and a calculated (2.5 X 40 mR measured ESE) ESE of 100 mR. Absorbed dose in Gy determined by 100 mR/100 mR per mGy = 1.00 mGy and 1.00 mGy/1,000mGy per 1 Gy = 0.0010 Gy. This value in Gy is used with DCF values from, Tables A-2 through A-9 from ICRP 34 (1982) to estimate organ dose conversion factors (mGy per Gy air kerma for a beam quality for 3.0 mm Al HVL). These DCFs were used to determine organ dose values for the listed organs in ICRP 34 (1982).

3.4 UNCERTAINTY ANALYSIS FOR NTS 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 factor is uncertainty, which is expressed in terms of a confidence level (e.g., 99% -- 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.

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
2. Variation in applied kilovoltage (kVp)
3. Variation in beam current (mA)
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, while potentially variable, would not affect the beam output intensity.

X-ray doses at NTS were largely derived from actual measurement of x-ray machine output with R-meters or similar ionization chamber devices (DeMarre 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.

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 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 might occur in line voltage input or other internal voltages, which in turn could alter the kVp of the output beam. In general, for a given kVp setting, variation in kVp falls within ±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 kilovoltage; this translates to an uncertainty of approximately ±8.6% with respect to output beam intensity in the 80 to 100 kVp used for diagnostic radiographs at NTS. For conservatism, this is rounded up to ±9%.

Similarly slight variations in tube current are normal; as a tube ages, or heats up from use, current can change and typically will drop. With all other factors constant, beam intensity will be reduced in direct proportion to the change in tube current. Typically, the reduction in beam output from current variation is not more than a few percent under normal operating conditions; large decreases are readily detectable and 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 NTS. 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 conservatively taken to be ±5%.

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

The final factor likely to affect worker dose relates to distance from the source of the x-rays, which is a determinant of the entrance skin exposure. 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 inverse square, this indicates an uncertainty of ±10% from this source.

There are two approaches to determine the combined uncertainty from the five potential sources of dose uncertainty listed above. The first, and most conservative in that it gives the greatest range, would be to assume that the uncertainties are additive, which would give an uncertainty range of 2 + 9 +5 + 25 + 10 = ±51%. However, a more reasonable approach would be to assume that the uncertainties are in fact random, and to compute the statistical root mean square (RMS) value. The RMS value is simply the square root of the sum of the squares, and computes as ±28.9%. Rounding this up to ±30% would seem to provide an adequate and suitably conservative indication of uncertainty. Thus, for an individual ESE or derived organ dose, an uncertainty of ±30% at the 99% confidence level can be assumed; for further conservatism it might be appropriate to assume that errors are all positive, and only +30% should be used.

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

Table 3-2. Organ doses for NTS 14" × 17" PA chest radiography for organs in ICRP 34 (1982). Doses are in rem.

Period	Frequency	Applicability	PA chest ESE[a]	Thyroid	Ovaries	Testes	Lungs	Breast	Uterus (embryo)	Bone marrow	Remainder
1951 to 1/1/1957[b]	Entrance										
	Exit										
	Biennial										
		All	125	2.16E-02	2.10E-02	1.14E-03	5.64E-02	6.13E-03	1.86E-02	1.15E-02	5.64E-02
1/1/57 to 3/31/2004	Entrance										
	Exit										
	Biennial										
		All	40	1.84-03	7.20E-05	4.00E-07	2.14E-02	2.76E-03	9.25E-05	4.68E-03	2.14E-02

a. Entrance skin exposure in mR.
b. Minimal collimation assumed before 1/1/57.

Table 3-2 (Continued). Organ doses for IREP organs not listed in ICRP 34 (1982). Doses are in rem.

Period	Frequency	Applicability	PA Chest ESE[a]	Thymus	Esophagus	Stomach	Bone surface	Liver/gall bladder/ spleen	Urinary/ bladder	Colon & rectum	Eye & brain	Skin[b]
1951 to1/1/1957	Entrance											
	Exit											
	Biennial											
		All	125	5.64E-02	5.64E-02	5.64E-02	5.64E-02	5.64E-02	2.10E-02	2.10E-02	2.16E-02	1.69E-01
1/1/57 to3/31/2004	Entrance											
	Exit											
	Biennial											
		All	40	2.14E-02	2.14E-02	2.14E-02	2.14E-02	2.14E-02	7.20E-05	7.20E-05	1.84E-03	5.60E-02

a. Entrance skin exposure in mR.
b. Skin dose was determined by multiplying the ESE by the backscatter factors of 1.35 and 1.4 (for HVLs of 2.5 and 3.0 mm Al respectively) from NCRP Report No. 102 (1989), Table B-8.

Table 3-3. Organ doses for NTS 14" × 17" Lateral chest radiography for organs in ICRP 34 (1982). Doses are in rem.

Period	Frequency	Applicability	Lateral chest ESE[a]	Thyroid[d]	Ovaries[d]	Testes[d]	Lungs[d]	Breast[d]	Uterus (embryo)[d]	Bone marrow[d]	Remainder
1951 to 1/1/1957[b]	Biennial	All	315	3.62E-02[c]	1.80E-02	1.04E-03	6.93E-02	8.03E-02	1.35E-02	1.17E-02	6.93E-02
1/1/57 to 3/31/2004	Biennial	All	100	1.33E-02	9.00E-05	1.00E-05	2.67E-02	2.87E-02	9.00E-05	4.80E-03	2.67E-02

a. Entrance skin exposure in mR.
b. Minimal collimation assumed prior to 1/1/1957.
c. The 14" × 17" lateral chest radiograph DCF for thyroid is greater than cervical spine DCF with a resultant greater dose. The larger organ dose is provided.
d. Organs identified in ICRP 34 (1982) for dose determination from ESE with radiography.

Table 3-3 (Continued). Organ doses for IREP organs not listed in ICRP (1982). Doses in rem.

Period	Frequency	Applicability	Lateral chest ESE[a]	Thymus	Esophagus	Stomach	Bone surface	Liver/gall bladder/ spleen	Urinary/ bladder	Colon & rectum	Eye & brain	Skin[b]
1951 to 1/1/1957	Annual	All	315	6.93E-02	6.93E-02	6.93E-02	6.93E-02	6.93E-02	1.80E-02	1.80E-02	3.62E-02	4.25E-01
1/1/57 to 3/31/2004	Annual	All	100	2.67E-02	2.67E-02	2.67E-02	2.67E-02	2.67E-02	9.00E-05	9.00E-05	1.33E-02	1.40E-01

a. Entrance skin exposure in mR.
b. Skin dose was determined by multiplying the ESE by the backscatter factors of 1.35 and 1.4 (for HVLs of 2.5 and 3.0mm Al, respectively) from NCRP Report No.102 (1989), Table B-8.

Table 3-4. Beam parameters for 14" × 17 " PA chest radiography.

Date measured	1/1/1957 to 1/31/2002	1951 to 1/1/1957
Procedure	Chest PA 14"×17"	Chest PA 14"×17"
Machine type	Unknown	Standard x-ray Model # EC-200
Machine settings kVp:	Unknown	72
mA	Unknown	200
Exposure time	Unknown	1/20 sec
mAs	Unknown	10
Added filter	2.5 mm Al	2.0 mm Al
HVL	3.0 mm Al	2.5 mm Al
Source to skin distance	72 "	72 "
Entrance skin exposure	40 mR from film badge readings	125 mR *from Gray (1996)
Reference	Personal communication M.DeMarre from film badge readings	NTS Medical x-ray equipment, Geiger, E. et al Health, Med Dept. REECO May 1960

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GLOSSARY

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).