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Draft	10/31/2003	00-A	New Technical Basis Document for the Fernald Environmental Management Project – Occupational Medical Dose. Initiated by Terry Kuykendall.
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ACRONYMS AND ABBREVIATIONS

AEC	automatic exposure control
Al	aluminum
AP	anterior-posterior
DHHS	State of Ohio Department of Human and Health Services
DOE	U.S. Department of Energy
EEOICPA	Energy Employees Occupational Illness Compensation Program Act of 2000
ESE	entrance skin exposure
FEMP	Fernald Environmental Management Project
FERMCO	Fernald Environmental Restoration Management Corporation
FMPC	Feed Material Production Center
Gy	gray
HVL	half value layer
ICRP	International Commission on Radiological Protection
ICRU	International Committee for Radiological Units
IREP	Interactive RadioEpidemiological Program
kVp	kilovolt peak
LAT	lateral
mA	milliampere
mAs	milliampere-sec
NBS	National Bureau of Standards
NCRP	National Council on Radiation Protection
NIOSH	National Institute for Occupational Safety and Health
OD	optical density
PA	posterior-anterior
RMS	root-mean-square
SID	source-to-image distance
SOP	Standard Operating Procedure
SSD	source-to-skin distance
TBD	technical basis document

3.0 OCCUPATIONAL MEDICAL DOSE

This section provides the technical basis for estimation of Fernald site worker radiological dose from exposure to occupational medical radiation sources.

The following criteria are applicable for the National Institute for Occupational Safety and Health (NIOSH) dose reconstruction program and this Technical Basis Document (TBD):

Only exposure to X-rays that were performed as a condition of employment is included; X-rays that resulted from injuries or medical testing are not included.

Medical exposures are assigned or assumed based on the actual or calculated frequency of chest X-rays required for employment.

There is no difference between the exposures experienced by unmonitored versus monitored workers since dosimeters normally worn by workers were not worn during diagnostic medical X-ray examinations. All exposures are external based on the assumption that internal radioisotopes were not administered for diagnostic purposes (with the exception that some radioisotopes might have been used at specific sites for stress testing as part of working conditions).

Specific organ doses to be attributed for posterior-anterior (PA) chest X-rays should be calculated on the basis of the dose conversion factors found in International Commission on Radiological Protection (ICRP) Publication 34 (ICRP 1982).

Organ doses from lateral chest radiography should be estimated at 2.5 times greater than those from the corresponding PA doses, based primarily on the greater mAs exposure per radiograph and the somewhat smaller source-to-skin distance (SSD). If technique factors can be identified for Type I equipment, organ doses for Type I equipment may be calculated by multiplying the organ dose estimates for Type II equipment by 2.5. This approach is reasonable when compared to other U.S. Department of Energy (DOE) sites (e.g., Hanford) where more information on X-ray equipment from the early period is available.

For organs not listed in ICRP (ICRP 1982) but specified in the Interactive RadioEpidemiological Program (IREP) code, doses should be determined by analogy with anatomical location. Using this logic, IREP code organs in the thoracic cavity that are not mentioned in ICRP (*ibid*) can be assigned the same dose as the lungs; doses to organs in the head and neck can be assigned the same dose as the thyroid. Head and neck organ (i.e., eye and brain) dose estimates should be somewhat greater than doses actually incurred (and therefore are claimant-favorable) because of geometry considerations and, at least in the case of the brain, because of attenuation by the bony cranium. To ensure claimant-favorability in view of the variations in organ dose described in ICRP (*ibid*, p. 51), apply the dose values for females, which are slightly higher than those for males.

For both PA and lateral views, a standard source-to-image distance (SID) of 72 inches (183 cm) may be assumed unless specifically noted otherwise.

If not specified, assume that all X-ray machines were single-phase and that there was no air gap between the patient and the film.

If there is an indication that mobile X-ray units were used, this could result in higher doses. This would imply that this type of unit (which could have been a photofluorographic machine) might have delivered higher exposures.

3.1 INTRODUCTION

The Fernald Environmental Management Project (FEMP, formerly known as the Feed Material Production Center, or FMPC) required pre-employment examinations and offered annual physical examinations as part of its occupational health and safety program. These medical examinations typically included diagnostic chest X-rays. Doses from these examinations depended not only on the characteristics of the X-ray machine and the procedure used, but also on the frequency of the examinations. The Energy Employees Occupational Illness Compensation Program Act of 2000 (EEOICPA) recognized that diagnostic medical X-rays administered in conjunction with routine or special physical examinations required for employment are a valid source of occupational exposure. This document describes the technical factors for and aspects of dose reconstruction from medical X-rays.

A number of factors determine doses to workers from diagnostic X-ray examinations. For a relatively standard medical radiographic (i.e., diagnostic) unit with a tungsten target (anode) and a focal spot of 1 to 2 mm, these factors involve the basic machine settings used for the exposure, which include the applied kilovoltage of the beam (kVp), beam current (mA), time of exposure, distance, waveform, amount and kind of filtration used, collimation or use of diaphragms, tube housing characteristics, type and speed of the film, development procedure, screens, grids, and the size of the worker.

3.1.1 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 produced in a typical medical X-ray tube are *bremsstrahlung* photons and, as such, are represented by 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 approximately 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, and are attenuated by the torso or other portion of the body being radiographed and never reach the film. These X-rays add very little to the radiography process, 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 in front of the X-ray 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 producing 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 an unfiltered spectrum, although the photon fluence rate is significantly reduced. Such a beam is typically referenced as having been *hardened*. A variation of this filtration technique is to use a higher applied kilovoltage and to filter the beam (relatively) heavily to eliminate most of the low-energy photons, which are of little radiographic value, from reaching the worker.

Beam energy is specified in terms of quality, or hardness, which in turn can be expressed in terms of the half value layer (HVL) in aluminum. Unfortunately, available documentation rarely presents this parameter. Even if the HVL is known, it might be of limited value in part because it does not specify the maximum energy of the beam or its true quality. This is 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 are commonly (although not always) available are the kVp of the machine and the external or added filtration. All X-ray tubes have “inherent” filtration, which is attributed to the window or port of the tube.

In medical diagnostic X-ray units, the window is thin (typically equivalent to 0.5 mm of aluminum in attenuation) and therefore provides little beam hardening.

Although the benefits of filtration for improved radiographic images were known and understood as early as March 1896 (within months of the discovery of X-rays), diagnostic radiographs were initially constructed with no added filtration. In 1937 the International Committee for Radiological Units (ICRU) recommended (although not specifically for thickness) aluminum filters for X-rays of 20 to 120 kVp, which includes the diagnostic X-ray energy range (ICRU 1937). Typical external filtration in the 1940s ranged from none to 1 mm of aluminum. This practice was in accordance with the 1936 recommendations of the U.S. Advisory Committee on X-Ray and Radium Protection (which became the National Council on Radiation Protection, or NCRP) that called for 0.5 mm of aluminum equivalent for radiographic installations and 1 mm of aluminum for fluoroscopy (NBS 1936). In 1949 the NCRP recommended 1 mm of aluminum filtration for radiography of thick parts of the body such as the chest (NBS1949). This filtration thickness was used in 100-mA units in large military hospitals during World War II, and presumably was applied to similar units at some DOE sites. In later applications the recommended filtration thicknesses were increased; in 1955, the NCRP guidance on diagnostic X-ray units recommended 2 mm of total aluminum filtration for new machines (NBS 1955). This increased in 1968 to 2.5 mm for medical diagnostic units operating above 70 kVp (NCRP 1968). Based on documentation of early measurements (November 20, 1961), FEMP used 2.5 mm of aluminum for the original X-ray unit since the start of operations.

The relationship of beam intensity[1] to applied kVp and filtration is complex and to some extent machine-specific and, therefore, is best determined empirically. However, in the absence of empirical data for a specific machine, there are adequate contemporary empirical and theoretical data on which to estimate machine output within a reasonable degree of uncertainty. Additional filtration reduces the entrance skin exposure (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 aluminum filtration will effect a reduction of approximately 40% in the ESE (Trout, Kelley, and Cathey 1952; Taylor 1957).

The approximate intensity reduction afforded by any thickness of aluminum filtration can be determined by the following exponential equation:

$$I = I_o e^{-0.5t} \qquad (3\text{–}1)$$

or

$$\ln (I/Io) = -0.5\ t \qquad (3\text{–}2)$$

where t is the thickness of aluminum in millimeters, and I and I_o are the beam intensities with and without the filter, respectively. In the absence of specific measurements or empirical data, this correction can be applied to determine the effect of filtration on beam intensity, and is consistent with the guidance in *External Dose Reconstruction Implementation Guideline* (NIOSH 2002).

Table 3-1 indicates the relationship of X-ray beam intensity and various technical factors.

Similarly, increasing the kVp will increase the beam intensity or exposure rate. This relationship can be calculated, but such calculations are difficult, complex, and time-consuming (even with the use of computer programs), and are at best approximations. However, many empirical studies of beam

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

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	$\pm$ 30 %	Assume all errors are positive, + 30% should be used

intensity as a function of kVp provide ample credible evidence to show that, for a given amount of filtration, increasing the applied kVp will increase the beam intensity according to the 1.7 power of the applied kilovoltage (Handloser 1951; Trout, Kelley, and Cathey 1952; Kathren 1965; BRH 1970). In the absence of specific measurements or empirical data, this function can be applied to determine the effect of applied kilovoltage on beam intensity, and is fully consistent with the NIOSH guidance (NIOSH 2002).

3.1.2 Current and Exposure Time

Diagnostic X-ray exposures typically are specified in terms of milliampere-seconds (mAs; the product of X-ray tube current and exposure time). All factors being equal (e.g., kVp, filtration, film, development and screen combination), radiation exposure is proportional to the number of mAs. The current in an X-ray tube refers to the number of electrons accelerated across the evacuated volume of the tube, flowing from the cathode to the anode. For a given applied kilovoltage, the number of X-ray photons produced and therefore the exposure (at least in theory) will be directly proportional to the X-ray tube current. This is and has been true for most medical radiography units over their design tube current range. Data from beam measurements conducted with medical radiographic X-ray units at FEMP are indicative of this linearity.

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 was increased proportionally to obtain the desired exposure in terms of mAs. From a dose reconstruction standpoint, earlier medical radiographic units had mechanical timers that were not as accurate as the electronic timers on later units. Gross bias errors in timer accuracy are unlikely because they would result in over- or underexposure of the radiograph and therefore would be quickly detected and corrected. Small random errors, which might produce uncertainties of as much as ±20% in the exposure, are more subtle. However, measurement data from the FEMP medical X-ray units give no indication or suggestion that the time or exposure parameters might be subject to a significant degree of error.

3.1.3 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) of 72 inches; *source* refers to the focal spot of the tube and *image* to the plane of the film. The distance to the worker, who was between the source and the film cassette, sometimes expressed in terms of the SSD, was smaller. 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 reaching 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 Bucky diaphragm, probably with a somewhat higher kVp. Based on this information, it might be appropriate for an individual dose reconstruction to increase the ESE for a large or stout worker.

3.1.4 Collimation and Waveform Characteristics

Among other factors that could affect worker dose are collimation and waveform. X-ray waveforms are of three types: half-wave rectified, which is rare; full-wave rectified, which is typical of medical radiographic units (and characteristic of units used at some DOE sites); and constant potential. A half-wave rectified machine produces 60 half-sinusoidal-shaped pulses of X-rays per second, each with duration of 1/120 of a second. A full-wave rectified machine produces 120 half-sinusoidal pulses per second, each with duration of 1/120 of a second. Therefore, for a given setting of kVp and mA, the intensity of the beam from a half-wave rectified machine is half that of the beam from a full-wave rectified unit. A constant potential machine produces a more or less steady (i.e., unpulsed) output of X-rays and has greater beam intensity (approximately 10% greater) compared to a full-wave rectified machine operating at the same kVp and mA. For FEMP, waveform is of no significance for determination of worker exposure because actual output measurement data are available.

Collimation refers to the size of beam. The early philosophy for radiography was to use a fairly large aperture with limited collimation to ensure that the entire area of interest was included in the radiograph. Later, because of health 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 conducted by examination of the radiograph.

On November 26, 2003, a telecommunications discussion was conducted with the current FEMP records manager, Mr. Brian Devir, who (as a request of the TBD investigation) selectively examined radiographs from chest X-rays taken from 1952 to 1980. He confirmed that a clearly distinct darkened area existed at the lower edge of each radiograph, which is specifically indicative of the use of collimation. Also noted was that all of the radiographs examined from the years 1952 to 1980 exhibited the same unexposed area at the edges. A well-collimated beam would have left a small, unexposed area or penumbra effect at the edges of the radiograph, while a poorly collimated beam would have produced a radiograph that was exposed over the entire area. Based on the discussions with Mr. Devir and the correlated evaluation of the radiograph files, it is possible to reach the conclusion that the X-ray beams used at FEMP were collimated from the beginning of the medical X-ray processes at the site, and should be treated as such when estimating the contribution of an individual due to medical X-ray exposure.

3.1.5 Screens, Grids, and Other Factors with the Potential to Affect Work Dose

A number of other factors affect the X-ray exposure required to obtain a proper radiograph and the attendant dose to the worker. Knowledge of these factors is unnecessary for dose reconstruction purposes if actual beam measurements are available, or if the primary machine characteristics of applied voltage, time, current, and amount of primary beam filtration are known. However, these other factors, which include housing, type and speed of film, development procedure, screens, and grids, can be used as additional confirmation of the applicability of the reconstructed dose.

X-ray tubes used for diagnostic radiography are typically enclosed in protective lead-shielded tube housings. The primary beam is transmitted through a port or window in the side of the housing. Although some reduction of dose to the worker is achieved, primarily through elimination of scattered

radiation and improved collimation, the main purpose of the tube housing is protection of the operator, unexposed X-ray film, and nearby individuals other than the worker. This issue should not be considered a factor for dose reconstruction because virtually all X-ray tubes used during the period of DOE operations (including the tubes assumed to be in use at DOE sites) were designed with protective tube housings.

The amount of exposure required for an acceptable diagnostic radiograph is to a certain degree a function of film speed and development. Fine grain emulsions produce a superior radiographic image but require additional exposure in comparison to fast films. Additional exposure might be required to achieve satisfactory radiographic quality and to avoid underdevelopment of films. Intensifying screens can be used in the cassette to intensify the radiographic effect, thereby increasing film speed and reducing worker dose. Grids, specifically the Potter-Bucky diaphragm (colloquially known as a Bucky) are sometimes used for thick section radiography, but rarely for chest radiography (except for large workers). These additional parameters are factored into the technique (i.e., kVp, mA) used and, except in rare instances and a virtually complete absence of other data, are not important in dose reconstruction.

3.1.6 Assumptions for Dose Conversion

A degree of confusion might have been engendered at many DOE sites and at various periods by the use of a variety of conversion coefficients to calculate exposure to absorbed dose. At various times an exposure of 1 R has been equated to a soft tissue dose of 0.83, 0.877, or 0.93 rad. Using these values, an exposure to air of 1 R would result in an absorbed dose of less than 1 rad (1 cGy = 10 mGy). However, regulations applicable to DOE sites have defined 1 R as equal to a dose of 1 rad (10 mGy). Using this value would produce an overestimate in the reported dose or dose equivalent because dosimeters were typically calibrated against a field measured in R, which was numerically equated as absorbed dose in rad (Kathren and Petersen 1989). Further complicating the conversion of ESE in terms of exposure to absorbed dose is the contemporary trend to refer to X-ray intensity in terms of the quantity *kerma*, which is measured in the same units as absorbed dose. Typically, the numerical value of kerma is slightly lower than the corresponding value of absorbed dose. Therefore, to ensure conservatism and compliance with NIOSH requirements (NIOSH 2002), and to avoid risk dose underestimation, 1 R of exposure was accepted as equal to1 rad of absorbed dose and to 1 rad (10 mGy) of kerma.

Conversion of exposure expressed as ESE has been conducted in accordance with published conversion coefficients in Tables A2 through A9 of ICRP 34 (ICRP 1982). These tables provide average absorbed organ doses for selected medical radiography procedures related to an entrance air kerma (without backscatter) of 1 Gy for various beam qualities expressed in terms of HVL of aluminum. However, the tables do not include all organs identified in the IREP code. For organs included in the IREP but not specifically identified in ICRP 34, application of the dose conversion coefficient for the anatomically analogous organ that is identified in ICRP 34 is a reasonable and simple first-order approach that generally would be claimant-favorable (or at least neutral). Using this approach, the factor for lungs would be applied to all other organs in the thoracic cavity (i.e., thymus, esophagus, liver, gall bladder 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, is in the trunk, the factor for lung would be applied to bone surfaces. The dose conversion factor for the ovary would be used for organs in the abdomen (i.e., urinary bladder and colon). For the eye, the analogous organ is the thyroid.

Based on the preceding discussion, a value of 1 R was equated to 10 mGy of kerma. Conversion is simple if the beam quality is known. Unfortunately, measured beam quality data were not identified in

the site documentation. However, the kVp and filtration are known and beam quality can be estimated from these data. Because exposure (mAs) as absorbed organ dose increases as a function of HVL for a given amount of filtration, the upper limit on the likely beam quality has been calculated and rounded upward (for conservatism) to match the closest value in the tables in ICRP 34.

Determination of dose requires consideration of two correlated factors: the HVL, which represents a function of peak tube potential; and added filtration, which is a function of the thickness of a filter added for beam hardening. The conservative value of HVL as a function of peak tube potential was used based on Table A16 in ICRP 34. For the period of October 1951 to February 1977, the beam quality as HVL and the value for added filtration both were expressed as 2.5 mm of aluminum (based on assumptions from measurements taken in November 1961). Starting in March 1977 until the present the reported added filtration is 3.0 mm of aluminum. From the period of March 1977 to February 1988, an HVL of 3.0 mm of aluminum was used for all organ dose estimates; this value was changed to 3.5 mm for the period of March 1988 until June 1999, and was changed to 4.0 mm from July 1999 until the present. Organ dose was determined by using the closest values in the tables A2 to A9 in ICRP 34.

3.2 EXAMINATION FREQUENCIES

The frequency of medical examinations varied over the years of FEMP operation. There is no evidence that occupational X-rays might have occurred more frequently than on the schedule indicated in Table 3-2. This table lists the frequencies of chest X-rays for different age groups over ranges of years and identifies the correlated groups of workers.

Table 3-2. Frequency of occupational chest X-rays at FEMP.

Period	Frequency	Comment
1952–1981	Annually	All employees
	Annually	Construction asbestos workers
1981–2002	Annually	Employees over 45 years old
	Every 2 years (offered)	Employees under 45 years old

In a review of claimant files, it was noted that approximately 15% of the claims reported a re-take of the chest X-ray.

It also was noted in reviewing claimant files that lumbar spine X-rays were taken primarily for construction worker and laborers. In a telephone communication with Mr. Louis C. Bogar, the former Vice President of ES&H for FEMP, on October 28, 2003, he clearly stated that lumbar spine X-rays and any X-rays other than chest were not taken as occupational or pre-employment requirements.

Several telephone communications were conducted with Ms. Betty Smith, a former registered nurse who worked at FEMP from1953 until 1993, and with Ms. Diane Jacobowski, a former X-ray technologist who worked at FEMP from 1986 to 2002, confirmed that no photofluorographic X-rays were performed at any time at FEMP.

3.3 EQUIPMENT AND TECHNIQUES

Although medical practices at FEMP are assumed to have followed the standards of radiology practice during the 1940s and later for minimizing worker dose, there has been the potential for significant dose from occupational medical X-ray examinations. The magnitude of this type of dose depends on the type of equipment, the technique factors, and the number of radiographic

examinations. Many FEMP medical records include notations on both the date and the purpose of X-ray examinations.

X-ray organ dose estimates for occupational X-rays administered at FEMP are calculated for Type I equipment (used from 1951 through 1983), Type II equipment (used from 1983 to March 1988), and Type III equipment (used from March 1983 to 2002). Table 3-3 summarizes the X-ray equipment used at FEMP.

Table 3-3. Description of FEMP X-ray equipment.

Technique	Period	Equipment
Type I	1951–1977	Keleket X-ray unit, 2.5-mm Al equivalent filtration, no grid, manual/hand processing, manual collimator.
Type II	1977-1988[2]	Bennett X-ray Corp. Model 300 Vet-7, manual/hand processing.
Type III	1988–2002	General Electric Company Model 46-2611-85G1, manual/hand processing.

Because no technique factors were clearly identified at FEMP for Type I equipment from the beginning of operations to February 24, 1977, organ doses based on assumed technique factors were developed by comparing X-ray techniques from the period (i.e., 1951 to 1977) with due consideration to claimant favorability. Accordingly, an operating kVp of 90 was assumed, which is somewhat higher (and therefore claimant-favorable) than the kVp values typically used at the time. External filtration was reported to be 2.5 mm of aluminum. The SSD was assumed to be 152 cm, based on a SID of 183 cm less a chest thickness of 26 cm and an addition of 5 cm to account for cassette thickness.

A survey was conducted in 1961 of diagnostic X-ray units and the associated radiation levels at various kVps and mAs. The purpose of this survey was to determine what radiation exposures would be recorded on the film badge during medical procedures at various kVps if the badge was inadvertently left on the individual or accidentally exposed to X-rays during medical procedures. Measurements were taken with a Victoreen condenser R-meter and compared to average output of diagnostic equipment from National Bureau of Standards (NBS) Handbook 76 (NBS 1961). If no measurements were provided, a dose was calculated using an average decrease of 22% estimated from other actual measurements. Table 3-4 lists the results of this survey as an aid for dose reconstruction of early (pre-1977) exposures.

Table 3-4. 1961 survey of X-ray units.*

kVp	mAs	Distance (inches)	Average exposure (R)	Measured exposure	% Decrease from avg.	Calculated dose (22%)
30	50	34	0.10	0.085	15	---
50	150	36	0.30	0.225	25	---
50	200	24	0.80	0.60	25	---
50	300	18	1.60	1.40	12	---
50	350	18	2.80	2.20	21	---
70	20	36	0.10	0.072	28	---
70	60	36	0.30	0.225	25	---
70	180	36	0.90	0.720	20	---
70	300	36	1.50	1.200	20	---
70	250	24	2.75	2.000	27	---
90	50	72	0.10	---		0.078
90	150	72	0.30	---		0.234
90	100	36	0.90	---		0.702
90	75	24	1.43	---		1.112
90	150	24	2.85	---		2.220

*Brown 2002, section labeled (A) --1961 Keleket X-ray, Unit Survey of X-ray Unit.

2. There is no data on the actual dates that the Bennett X-ray unit was in operation; therefore, the measured data from February 1977 was applied from the period of 1977 to 1988.

A conservative exposure time for the period before February 24, 1977, can be estimated in the order of 20 mAs. There is no indication that FEMP used voltages higher than 90 kVp for PA chest X-rays during this period. ESE for the period before 1977 was calculated based on average exposure level of 100 mR/hr for 50 mAs at 183 cm and adjusted to 20mAs at 152cm. The calculations conservatively estimate the ESE to be 58.0 mR.

A series of measurements were performed on February 24, 1977, to determine the ESE that would be received during a medical X-ray of various body parts based on the X-ray techniques used at FEMP. Table 3-5 lists the conditions for these calculations.

Table 3-5. X-ray conditions and power used.*

Location	Body part thickness (cm)	Filter (mm Al)	Distance (inches)	kVp	mAs
Chest (PA)	23	3.0	72	74	6.7
Skull (lateral)	15	3.0	40	78	60
Cervical spine (AP)	13	3.0	40	70	40
Thoracic spine (AP)	23	3.0	40	81	100
Lumbar spine (AP)	23	3.0	40	70	150
Foot (DP)	8	3.0	40	44	100
Abdomen (AP)	23	3.0	40	76	60

* Brown 2002, section labeled (B) Entrance Skin Exposure From Medical X-rays.

The measurements were performed to assure management that exposures for all X-rays of interest were less than the proposed ESE Guides published in the *Federal Register* (Vol. 42, No 17, January 26, 1977, p. 4884). Table 3-6 presents the results of these measurements.

Table 3-6. Calculated and measured results of entrance skin exposure and comparison with proposed guides.*

Location	mR/mAs	Entrance skin exposure (mR)	Proposed exposure guide
Chest (PA)	1.7	11.4	30
Skull (lateral)	4.65	279	300
Cervical spine (AP)	3.68	147	250
Thoracic spine (AP)	5.08	508	900
Lumbar spine (AP)	3.67	551	1,000
Foot (DP)	1.08	108	270
Abdomen (AP)	4.38	263	750

*Brown 2002, section labeled (B) Entrance Skin Exposure From Medical X-rays.

Using the reported information from the series of measurements performed in February 1977, a value of 10 mAs of exposure time for an extra large man is used in the conservative estimate of the ESE. Therefore, the estimate of the ESE from the period of March 1977 to February 1988 is 1.7 mR/mAs times 10 mAs to determine an ESE of 17.0 mR.

In July 1987, Standard Operating Procedure (SOP) ESH-P-12-004, “Preparation and Activation of a Diagnostic X-ray,” was issued (Brown 2002). A summary of the techniques cited in this report is provided in Table 3-7. An implemented policy stated that chest X-rays were mandatory for preemployment physicals and were available annually thereafter. Other X-ray(s) were performed as required by a physician. Female candidates were required to read and sign a pregnancy form that was included in her personnel/employment file. An individual wishing to exercise the option to not accept the chest X-ray offered as part of the annual physical was required to read and sign an X-ray refusal form.

Table 3-7. X-ray techniques (issue date 7/23/87).*

Location	Milliamp (mA)	Time (sec)	kVp	mAs	Subject
Chest	PA-100	1/30	80-84	3	Avg. woman
	PA-100	1/15	80-84	6	Lg. woman
	LAT-100	1/15	90-100	6	Avg. woman
	PA-100	1/20	80	5	Avg. man
	PA-100	1/15	90	6	Lg. man
	PA-100	1/10	85-90	10	X-lg. man
	LAT-100	1/10	100-115	10	Avg. man

*Brown 2002, section labeled (F) "Preparation and Activation of a Diagnostic X-ray."

In March of 1988 FEMP purchased a new General Electric X-ray system. The calculated entrance skin exposure for this unit was approximately 12.2 mR. The ESE was calculated with the technique factor of 100kVp, 5.0 mAs, (160 mA and 0.033 second); this represents the technique typically set by the technologist.

Beginning January 30, 1991, the State of Ohio Department of Health and Human Services (DHHS) conducted diagnostic X-ray assurance surveys that included an evaluation of the chest projection technique/exposure. A LuCal chest phantom was used for all of the exposure measurements. The measured results of the entrance skin exposure for subsequent years are listed in Table 3-8.

Table 3-8. Measured entrance skin exposures. *

Year	kVp	mAs	SID, in.	Entrance skin exposure
1991	100	5.0	72	12.2 mR (AEC)**
1993	100	5.0	72	15.3 mR (AEC)
1995	110	8	72	28.0 mR (Manual)
1997	126	8	72	17.5 mR (AEC)
1997	110	8	72	32.2 mR (Manual)
2000	126	6.4	72	30.2 mR (Manual)

*Brown 2002, section labeled Exposure Survey Results – Bi-ennial FDA inspections
**Calculated by DHHS on January 22, 1991

The use of different film screen systems and automatic exposure control (AEC) versus manual operation can cause a significant difference in entrance skin exposure. Measurements performed during the early years, as noted in Table 3-8, used AEC. Occupational medical X-rays on workers might have used manual settings. For the values in this TBD section, the higher value reported was applied to estimate organ doses.

A 1995 survey by the DHHS noted a significant increase in the entrance skin exposure over the 1993 survey (i.e., from 15.3 mR to 28.0 mR). The FEMP response was that since the 1993 inspection (and following a risk/benefit analysis) FEMP had switched (for approximately 1 year) to the Kodak InSight Thoracic Imaging System. This system was designed to improve overall clinical performance related to chest examinations. It enabled FEMP to obtain significantly more usable information during a single session in comparison to the former "conventional" imaging system. The new system required changes in equipment settings (i.e., the technique) to accommodate and allow for the best diagnostic utilization of the technically superior film. The "increased" measured ESE of 28 mR using the new technology was still below the recommended Federal ESE guideline of 30 mR for routine chest radiography.

A 1997 DHHS survey found that the measured ESE was 32.2 mR. The technique used was a manual mode at 110 kVp and 8 mAs. The survey noted that the film optical density (OD) was outside the

defined range. DHHS recommended that FEMP contact the service representative for the X-ray system and the Kodak film representative to discuss methods to lower patient ESE, and change exposure techniques from a manual to a phototimed process. FEMP made the recommended changes to improve the OD, and in a return inspection DHHS measured the ESE to be 19.2 mR. The technique used was 4 mAs at 126 kVp. For the assessment of organ doses during this period, the higher ESE of 32.2mR was used.

In a July 1, 1999 survey, DHHS determined that the (apparently) continued manual techniques at FEMP yielded an ESE for PA chest X-ray of 30.2 mR at 6.4 mAs and 126 kVp. The same test using the AEC at 126 kVp found the ESE to be 16.4 mR for a film density of 1.24. In the AEC mode, the optical density was well outside the recommended range. DHHS recommended continuing the use of the manual mode.

In an April 13, 2000, DHHS survey, the ESE for PA chest X-ray was 30.2 mR. The manual technique, 126 kVp and 6.4 mAs, was used for this survey. DHHS did not recommend any changes.

Table 3-10 at the end of this TBD section summarizes the X-ray beam parameters for 14- x 17-in PA chest radiography examinations.

3.4 ORGAN DOSE CALCULATIONS

Tables 3-11 and 3-12 at the end of this TBD section list specific organ doses to be attributed for PA chest X-rays calculated on the basis of the dose conversion factors provided in ICRP 34.

Organ doses from lateral chest radiography have been estimated at 2.5 times greater than those from corresponding PA doses, based primarily on the greater mAs exposure per radiograph and the somewhat smaller SSD. For organs not listed in the ICRP reference (ICRP 1982) but specified in the IREP code, doses were determined by analogy with anatomical location, as listed in Table 3-9.

Table 3-9. Analogues for IREP organs not in ICRP 34.

Anatomical location	ICRP 34 reference organ	IREP organ analogues
Thorax	Lung	Thymus; esophagus; stomach; bone surface; liver/gall bladder; remaining organs
Abdomen	Ovaries	Urinary system/bladder; colon/rectum
Head and neck	Thyroid	Eye/brain

Based on this approach, IREP code organs in the thoracic cavity but not mentioned in ICRP 34 were assigned the same dose as the lungs; doses to the organs in the head and neck should be assigned the same dose as the thyroid. The head and neck organ dose estimates (i.e., eye/brain) should be slightly greater than doses actually incurred (and therefore claimant-favorable) because of geometry considerations and, at least in the case of the brain, because of attenuation by the bony cranium.

Skin doses were determined by multiplying the ESE by the backscattering factor (1.4 HLVs for 4.0 mm of aluminum) from NCRP data (NCRP 1985, Table B-8).

Tables 3-13 through 3-19 at the end of this TBD section summarize organ dose data for FEMP occupational medical exposures.

3.5 UNCERTAINTY

Error, defined as 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 the correct or actual; therefore, the more appropriate term is uncertainty, which is expressed in terms of a confidence level, e.g., 99% (i.e., 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 approaches the actual or correct value.

Although in theory a large number of factors can introduce uncertainties or affect the X-ray machine output intensity and dose to the patient, in practice only four factors can reasonably have a significant impact on dose uncertainty: variation in applied kilovoltage, variation in beam current, variation in exposure time, and distance from the patient to the source of the X-rays (SSD). The influence of other factors such as the use of screens, grids, reciprocity failure, film speed, and development, while potentially variable, would not affect the beam output intensity.

For a given set of machine settings and parameters, X-ray output theoretically should be constant and unvarying. However, this is not true in practice, although output is essentially constant unless focal spot loading occurs, as when the power rating of the machine is exceeded. It is unlikely that power ratings were ever exceeded; this would have been difficult to achieve in practice and would have resulted in damage to the X-ray tube. However, even with the use of "constant voltage" transformers to control line voltages, slight variations could have occurred in line voltage input or other internal voltages, which in turn could have altered the kVp of the output beam. In general, for a given kVp setting, variation in kVp falls within ±5% of the machine setting. Because beam intensity is approximately proportional to the 1.7 power of the kilovoltage, this translates to an uncertainty of approximately ±8.7% for output beam intensity in the 100- to 120-kVp range used for diagnostic radiographs at FEMP. For conservatism, this is rounded up to ±9%.

Similar, slight variations in tube current are normal; as a tube ages, or heats from use, tube current can change and typically will drop. Therefore, with all other factors remaining 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 in beam output will be readily detected 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 these measures were ever necessary or applied at FEMP. For a given kVp setting, the output of the beam is a function of tube current, which in turn is measured by a milliammeter on the machine. The measurement is subject to uncertainties, and there might be minor changes in output as the tube heats from normal use. Because these variations are typically small, uncertainty in beam output attributable to current variation has been estimated at ±5%.

Another parameter that can affect the dose, perhaps significantly, from a diagnostic radiograph relates to the time of exposure. This can be understood by noting that a full-wave rectified machine produces 120 pulses per second of X-rays. For 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 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, and timer accuracy improved significantly with the introduction of electronic timers. However, for conservatism, uncertainty in beam output attributable to timers will be assumed to have an upper limit of +25%.

The final factor that is 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 the thickness of the patient, and the accuracy of the positioning. For a typical patient, this variation in SSD is estimated at no more than a few centimeters, with an upper limit of perhaps 7.5 cm. Using inverse square calculations, this indicates an uncertainty of ±10% from this source.

There are two approaches to determine the combined uncertainty from the four potential sources of uncertainty discussed 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 up to 9 + 5 + 25 + 10 = 49. 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 ±28.7%. Therefore, for an individual ESE or derived organ dose, an uncertainty of ±30% at the 1 sigma level can be assumed. For further conservatism it might be appropriate to assume that errors are all positive, and only +30% should be used.

One annual X-ray procedure for each full or partial year of employment is assumed. However, if the dose reconstructor determines that more frequent procedures occurred or might have occurred, the annual organ doses can be increased accordingly.

Table 3-10. Summary of beam parameters for 14" × 17 " PA chest radiography.

Date measured	4/2000	7/1999	5/1997	3/1995	4/1993	1/1991	2/1977	11/1961
Procedure	Chest PA 14"×17"	Chest PA 14"×17"	Chest PA 14"×17"	Chest PA 14"×17"	Chest PA 14"×17"	Chest PA 14"×17"	Chest PA 14"×17"	Chest PA 14"×17"
Machine type	GE Model 46	GE Model 46	GE Model 46	GE Model 46	GE Model 46	GE Model 46	Bennett 300	Keleket
Machine settings kVp:	126	126	110	110	100	100	90	90
mA	200	200	100	100	100	100	100	150
Exposure time	1/30 sec	1/30 sec	1/30 sec	1/20 sec	1/20 sec	1/20 sec	1/10 sec	1/15 sec
mAs	6,4	6.4	8 (m)	8	5	5	10	20
Added filter	3.0 mm	3.0 mm	3.0 mm	3.0 mm	3.0 mm	3.0 mm	3.0 mm	2.5 mm
HVL (filtration used for calculations)	4.0 mm	4.0 mm	3.5 mm	3.5 mm	3.5 mm	3.5 mm	3.0 mm	2.5 mm
Skin to image distance	183 cm	183 cm	183 cm	183 cm	183 cm	183 cm	183 cm	183 cm
Entrance skin exposure	30.2 mR	30.2 mR	32.2 mR	28 mR	15.3 mR	12.2 mR	17.0 mR	58.0 mR (assumed)
mR/mAs	4.7	4.7	4.0	3.5	3.1	2.4	1.7	1.6
Date range		7/99-present	4/95-6/99	5/93-3/95	2/91-4/93	3/88-1/91	3/77-2/88*	10/51-2/77
Reference source	DHHS	FERMCO**	DHHS	DHHS	DHHS	DHHS	NLO***, FMPC	FMPC

* There is no data on the actual dates that the Bennett X-ray unit was in operation; therefore, the measured data from 02/77 was applied from the period of 03/77 to 02/88.
** Fernald Environmental Restoration Management Corp, or FERMCO.
*** National Lead of Ohio, Inc.

Table 3-11. Average absorbed chest X-ray dose (mGy) for selected organs for 1 Gy entrance kerma (air kerma without backscatter) for a beam quality of 2.5 mm of aluminum (HVL).[a]

Organ	View	Source-image distance (cm)	Image receptor size (cm)	Dose conversion factor (mGy per Gy air kerma; beam quality 2.5 mm aluminum HVL)
Thyroid	PA	183	35.6 × 43.2	32
	Lat.	183	35.6 × 43.2	115
Ovaries	PA	183	35.6 × 43.2	1
	Lat.	183	35.6 × 43.2	0.6
Testes	PA	183	35.6 × 43.2	0.01
	Lat.	183	35.6 × 43.2	0.1
Lungs (male)	PA	183	35.6 × 43.2	419
	Lat.	183	35.6 × 43.2	193
Lungs (female)	PA	183	35.6 × 43.2	451
	Lat.	183	35.6 × 43.2	220
Breast	PA	183	35.6 × 43.2	49
	Lat.	183	35.6 × 43.2	255
Uterus	PA	183	35.6 × 43.2	1.3
	Lat.	183	35.6 × 43.2	0.6
Bone marrow (male)	PA	183	35.6 × 43.2	92
	Lat.	183	35.6 × 43.2	37
Bone marrow (female)	PA	183	35.6 × 43.2	86
	Lat.	183	35.6 × 43.2	29
Total body (male)	PA	183	35.6 × 43.2	131
	Lat.[b]	183	35.6 × 43.2	64
Total body (female)	PA	183	35.6 × 43.2	118
	Lat.	183	35.6 × 43.2	60

a. Dose conversion factors from Tables A.2 through A.9 from ICRP (1982).

Table 3-12. Average absorbed chest X-ray dose (mGy) for selected organs for 1 Gy entrance kerma (air kerma without backscatter) for a beam quality of 3.0 mm of aluminum (HVL).[a]

Organ	View	Source-image distance (cm)	Image receptor size (cm)	Dose conversion factor (mGy per Gy air kerma; beam quality 3.0 mm aluminum HVL)
Thyroid	PA	183	35.6 × 43.2	46
	Lat.	183	35.6 × 43.2	133
Ovaries	PA	183	35.6 × 43.2	1.8
	Lat.	183	35.6 × 43.2	0.9
Testes	PA	183	35.6 × 43.2	0.01
	Lat.	183	35.6 × 43.2	0.1
Lungs (male)	PA	183	35.6 × 43.2	496
	Lat.	183	35.6 × 43.2	236
Lungs (female)	PA	183	35.6 × 43.2	535
	Lat.	183	35.6 × 43.2	267
Breast	PA	183	35.6 × 43.2	69
	Lat.	183	35.6 × 43.2	287
Uterus	PA	183	35.6 × 43.2	2.3
	Lat.	183	35.6 × 43.2	0.9
Bone marrow (male)	PA	183	35.6 × 43.2	117
	Lat.	183	35.6 × 43.2	48
Bone marrow (female)	PA	183	35.6 × 43.2	112
	Lat.	183	35.6 × 43.2	38
Total body (male)	PA	183	35.6 × 43.2	153
	Lat.	183	35.6 × 43.2	83
Total body (female)	PA	183	35.6 × 43.2	145
	Lat.	183	35.6 × 43.2	77

a. Dose conversion factors from Tables A.2 through A.9 from ICRP (1982).

Table 3-13. Organ dose estimates for FEMP chest radiographs from 10/1951 to 1/1977.

Organ	View	Organ dose (mGy)	Organ dose (rem)
Thyroid	PA	1.86E-02	1.86E-03
	Lat.	6.68E-02	6.68E-03
Ovaries	PA	5.80E-04	5.80E-05
	Lat.	3.48E-04	3.48E-05
Testes	PA	5.80E-06	5.80E-07
	Lat.	2.90E-05	2.90E-06
Lungs (male)	PA	2.44E-01	2.44E-02
	Lat.	1.12E-01	1.12E-02
Lungs (female)	PA	2.60E-01	2.60E-02
	Lat.	1.28E-01	1.28E-02
Breast	PA	2.86E-02	2.86E-03
	Lat.	1.31E-01	1.31E-02
Uterus	PA	7.56E-04	7.56E-05
	Lat.	3.48E-04	3.48E-05
Bone marrow (male)	PA	5.34E-02	5.34E-03
	Lat.	2.14E-02	2.14E-03
Bone marrow (female)	PA	4.98E-02	4.98E-03
	Lat.	1.68E-02	1.68E-03
Total body (male)	PA	7.56E-02	7.56E-03
	Lat.	3.72E-02	3.72E-03
Total body (female)	PA	6.84E-02	6.84E-03
	Lat.	3.48E-02	3.48E-03
Skin		8.14E-01	8.14E-02

Table 3-14. Organ dose estimates for FEMP chest radiographs from 2/1977 to 2/1988.

Organ	View	Organ dose (mGy)	Organ dose (rem)
Thyroid	PA	7.80E-03	7.80E-04
	Lat.	2.25E-02	2.25E-03
Ovaries	PA	3.04E-04	3.04E-05
	Lat.	1.52E-04	1.52E-05
Testes	PA	1.69E-06	1.69E-07
	Lat.	1.69E-05	1.69E-06
Lungs (male)	PA	8.40E-02	8.40E-03
	Lat.	4.00E-02	4.00E-03
Lungs (female)	PA	9.05E-02	9.05E-03
	Lat.	4.51E-02	4.51E-03
Breast	PA	1.17E-02	1.17E-03
	Lat.	4.86E-02	4.86E-03
Uterus	PA	3.90E-04	3.90E-05
	Lat.	1.52E-04	1.52E-05
Bone marrow (male)	PA	1.98E-02	1.98E-03
	Lat.	8.13E-03	8.13E-04
Bone marrow (female)	PA	1.89E-02	1.89E-03
	Lat.	6.44E-03	6.44E-04
Total body (male)	PA	2.59E-02	2.59E-03
	Lat.	1.40E-02	1.40E-03
Total body (female)	PA	2.37E-02	2.37E-03
	Lat.	1.30E-02	1.30E-03
Skin		2.37E-01	2.37E-02

Table 3-15. Organ dose estimates for FEMP chest radiographs from 3/1988 to 1/1991.

Organ	View	Organ dose (mGy)	Organ dose (rem)
Thyroid	PA	7.57E-03	7.57E-04
	Lat.	1.85E-02	1.85E-03
Ovaries	PA	3.92E-04	3.92E-05
	Lat.	1.96E-04	1.96E-05
Testes	PA	1.22E-05	1.22E-06
	Lat.	1.22E-04	1.22E-05
Lungs (male)	PA	6.87E-02	6.90E-03
	Lat.	3.37E-02	3.37E-03
Lungs (female)	PA	7.44E-02	7.44E-03
	Lat.	3.78E-02	3.78E-03
Breast	PA	1.11E-02	1.11E-03
	Lat.	3.85E-02	3.85E-03
Uterus	PA	3.65E-04	3.65E-05
	Lat.	1.72E-04	1.72E-05
Bone marrow (male)	PA	1.79E-02	1.79E-03
	Lat.	7.43E-03	7.43E-04
Bone marrow (female)	PA	1.71E-02	1.71E-03
	Lat.	5.85E-03	5.85E-04
Total body (male)	PA	2.12E-02	2.12E-03
	Lat.	1.14E-02	1.14E-03
Total body (female)	PA	1.96E-02	1.96E-03
	Lat.	1.09E-02	1.09E-03
Skin		1.71E-01	1.71E-02

Table 3-16. Organ dose estimates for FMPC chest radiographs from 2/1991 to 4/1993.

Organ	View	Organ dose (mGy)	Organ dose (rem)
Thyroid	PA	9.50E-03	9.50E-04
	Lat.	2.31E-02	2.31E-03
Ovaries	PA	4.90E-04	4.90E-05
	Lat.	2.44E-04	2.44E-05
Testes	PA	1.53E-06	1.53E-07
	Lat.	1.53E-05	1.53E-06
Lungs (male)	PA	8.65E-02	8.65E-03
	Lat.	4.24E-02	4.24E-03
Lungs (female)	PA	9.33E-02	9.33E-03
	Lat.	4.73E-02	4.73E-03
Breast	PA	1.40E-02	1.40E-03
	Lat.	4.83E-02	4.83E-03
Uterus	PA	4.58E-04	4.58E-05
	Lat.	2.14E-04	2.14E-05
Bone marrow (male)	PA	2.24E-02	2.24E-03
	Lat.	9.33E-03	9.33E-04
Bone marrow (female)	PA	2.15E-02	2.15E-03
	Lat.	7.33E-03	7.33E-04
Total body (male)	PA	2.71E-02	2.71E-03
	Lat.	1.44E-02	1.44E-03
Total body (female)	PA	2.46E-02	2.46E-03
	Lat.	1.36E-02	1.36E-03
Skin		2.14E-01	2.14E-02

Table 3-17. Organ dose estimates for FMPC chest radiographs from 5/1993 to 3/1995.

Organ	View	Organ dose (mGy)	Organ dose (rem)
Thyroid	PA	1.74E-02	1.74E-03
	Lat.	4.24E-02	4.24E-03
Ovaries	PA	8.95E-04	8.95E-05
	Lat.	4.47E-04	4.47E-05
Testes	PA	2.80E-06	2.80E-07
	Lat.	2.80E-05	2.80E-06
Lungs (male)	PA	1.58E-01	1.58E-02
	Lat.	7.75E-02	7.75E-03
Lungs (female)	PA	1.71E-01	1.71E-02
	Lat.	6.44E-02	6.44E-03
Breast	PA	2.56E-02	2.56E-03
	Lat.	8.84E-02	8.84E-03
Uterus	PA	8.39E-04	8.39E-05
	Lat.	3.92E-04	3.92E-05
Bone marrow (male)	PA	4.10E-02	4.10E-03
	Lat.	1.71E-03	1.71E-04
Bone marrow (female)	PA	3.94E-02	3.94E-03
	Lat.	1.35E-02	1.35E-03
Total body (male)	PA	4.88E-02	4.88E-03
	Lat.	2.62E-02	2.62E-03
Total body (female)	PA	4.51E-02	4.51E-03
Skin		3.92E-01	3.92E-02

Table 3-18. Organ dose estimates for FMPC chest radiographs from 4/1995 to 6/1999.

Organ	View	Organ dose (mGy)	Organ dose (rem)
Thyroid	PA	2.00E-02	2.00E-03
	Lat.	4.82E-02	4.82E-03
Ovaries	PA	1.03E-03	1.03E-04
	Lat.	5.14E-04	5.14E-05
Testes	PA	3.22E-06	3.22E-07
	Lat.	3.22E-05	3.22E-06
Lungs (male)	PA	1.82E-01	1.82E-02
	Lat.	8.90E-02	8.90E-03
Lungs (female)	PA	1.96E-01	1.96E-02
	Lat.	9.95E-02	9.95E-03
Breast	PA	2.94E-02	2.94E-03
	Lat.	1.02E-01	1.02E-02
Uterus	PA	9.63E-04	9.63E-05
	Lat.	4.51E-04	4.51E-05
Bone marrow (male)	PA	4.71E-02	4.71E-03
	Lat.	1.97E-02	1.97E-03
Bone marrow (female)	PA	4.54E-02	4.54E-03
	Lat.	1.54E-02	1.54E-03
Total body (male)	PA	5.60E-02	5.60E-03
	Lat.	3.02E-02	3.02E-03
Total body (female)	PA	5.18E-02	5.18E-03
	Lat.	2.87E-02	2.87E-03
Skin		4.51E-01	4.51E-02

Table 3-19. Organ dose estimates for FMPC chest radiographs from 7/1999 to present.

Organ	View	Organ dose (mGy)	Organ dose (rem)
Thyroid	PA	2.48E-02	2.48E-03
	Lat.	5.23E-02	5.23E-03
Ovaries	PA	1.65E-03	1.65E-04
	Lat.	7.95E-04	7.95E-05
Testes	PA	3.20E-06	3.20E-07
	Lat.	3.20E-05	3.20E-06
Lungs (male)	PA	2.02E-01	2.02E-02
	Lat.	9.53E-02	9.53E-03
Lungs (female)	PA	2.15E-01	2.15E-02
	Lat.	1.12E-01	1.12E-02
Breast	PA	3.71E-02	3.71E-03
	Lat.	1.10E-01	1.10E-02
Uterus	PA	1.66E-03	1.66E-04
	Lat.	6.69E-04	6.69E-05
Bone marrow (male)	PA	5.68E-02	5.68E-03
	Lat.	2.43E-02	2.43E-03
Bone marrow (female)	PA	5.50E-02	5.50E-03
	Lat.	1.89E-02	1.89E-03
Total body (male)	PA	6.10E-02	6.10E-03
	Lat.	3.39E-02	3.39E-03
Total body (female)	PA	5.68E-03	5.68E-03
	Lat.	3.16E-02	3.16E-03
Skin		4.23E-01	4.23E-02

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GLOSSARY

dosimeter
A device used to measure the quantity of radiation received. A holder with radiation-absorbing elements (filters) and an insert with radiation-sensitive elements packaged to provide a record of absorbed dose or dose equivalent received by an individual.

dosimetry
The science of assessing absorbed dose, dose equivalent, effective dose equivalent, etc., from external and/or internal sources of radiation.

exposure
As used in the technical sense, exposure refers to a measure expressed in roentgens (R) of the ionization produced by photon radiation (i.e., X-rays) in air.

Gray (Gy)
The special name for the SI unit of absorbed dose. (1 Gy = 1 Jkg^{-1}).

optical density
The quantitative measurement of photographic blackening; the optical density is defined as D = Log_{10} (I_o/I).

photon - X ray
Electromagnetic radiation of energies between 10 keV and 100 keV whose source can be an X-ray machine or radionuclide.

rad
The unit of absorbed dose**.**

radiation
Alpha, beta, neutron, and photon radiation.

rem
The rem is a unit of dose equivalent, which is equal to the product of the number of rad absorbed and the "quality factor."

Roentgen (R or r)
A unit of exposure to gamma or X-ray radiation. It is defined precisely as the quantity of gamma or X-ray radiation that will produce a total charge of 2.58 x 10^{-4} coulomb in 1 kg of dry air STP. An exposure of 1 R is approximately equivalent to an absorbed dose of 1 rad in soft tissue for higher (~>100 keV) energy photons.

shielding
Any material or obstruction that absorbs (or attenuates) radiation and thus tends to protect personnel or materials from radiation.

X-ray
Ionizing electromagnetic radiation of external nuclear origin or a radiograph.