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PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
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09/26/2006	01	Revised as a result of biennial review. Approved Revision 01. Constitutes a total rewrite of the document. Incorporates internal formal review comments. Incorporates NIOSH formal review comments. This revision results in a reduction in assigned dose and no PER is required. Training required: As determined by the Task Manager. Initiated by Daniel S. Mantooth.
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ACRONYMS AND ABBREVIATIONS

AP	anterior-posterior (X-ray projection)
cGy	centigray
cm	centimeter
DCF	dose conversion factor
DOE	U.S. Department of Energy
EEOICPA	Energy Employees Occupational Illness Compensation Program Act
GE	General Electric Corporation
Gy	gray
HVL	half-value layer
ICRP	International Commission on Radiological Protection
in.	inch
IREP	Interactive RadioEpidemiological Program
kVp	applied kilovoltage
LAT	lateral (X-ray projection)
mA	milliampere
mAs	milliampere second
mm	millimeter
mR	milliroentgen
mrad	millirad
mrem	millirem
NIOSH	National Institute for Occupational Safety and Health
PA	posterior-anterior (X-ray projection)
PGDP	Paducah Gaseous Diffusion Plant
POC	probability of causation
s	second
SID	source-to-image distance
SSD	source-to-skin distance
TBD	technical basis document
U.S.C.	United States Code
yr	year
§	Section

3.1 INTRODUCTION

3.1.1 Purpose

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

In this document the word "facility" is used as a general term for an area, building, or group of buildings that served a specific purpose at a site. It does not necessarily connote an "atomic weapons employer facility" or a "Department of Energy [DOE] facility" as defined in the Energy Employees Occupational Illness Compensation Program Act [EEOICPA; 42 U.S.C. § 7384l(5) and (12)]. EEOICPA defines a DOE facility as "any building, structure, or premise, including the grounds upon which such building, structure, or premise is located … in which operations are, or have been, conducted by, or on behalf of, the Department of Energy (except for buildings, structures, premises, grounds, or operations … pertaining to the Naval Nuclear Propulsion Program)" [42 U.S.C. § 7384l(12)]. Accordingly, except for the exclusion for the Naval Nuclear Propulsion Program noted above, any facility that performs or performed DOE operations of any nature whatsoever is a DOE facility encompassed by EEOICPA.

For employees of DOE or its contractors with cancer, the DOE facility definition only determines eligibility for a dose reconstruction, which is a prerequisite to a compensation decision (except for members of the Special Exposure Cohort). The compensation decision for cancer claimants is based on a section of the statute entitled "Exposure in the Performance of Duty." That provision [42 U.S.C. § 7384n(b)] says that an individual with cancer "shall be determined to have sustained that cancer in the performance of duty for purposes of the compensation program if, and only if, the cancer … was at least as likely as not related to employment at the facility [where the employee worked], as determined in accordance with the POC [probability of causation[1]] guidelines established under subsection (c) …" [42 U.S.C. § 7384n(b)]. Neither the statute nor the probability of causation guidelines (nor the dose reconstruction regulation) define "performance of duty" for DOE employees with a covered cancer or restrict the "duty" to nuclear weapons work.

As noted above, the statute includes a definition of a DOE facility that excludes "buildings, structures, premises, grounds, or operations covered by Executive Order No. 12344, dated February 1, 1982 (42 U.S.C. 7158 note), pertaining to the Naval Nuclear Propulsion Program" [42 U.S.C. § 7384l(12)]. While this definition contains an exclusion with respect to the Naval Nuclear Propulsion Program, the section of EEOICPA that deals with the compensation decision for covered employees with cancer [i.e., 42 U.S.C. § 7384n(b), entitled "Exposure in the Performance of Duty"] does not contain such an exclusion. Therefore, the statute requires NIOSH to include all occupationally derived radiation exposures at covered facilities in its dose reconstructions for employees at DOE facilities, including radiation exposures related to the Naval Nuclear Propulsion Program. As a result, all internal and external dosimetry monitoring results are considered valid for use in dose reconstruction. No efforts are made to determine the eligibility of any fraction of total measured exposure for inclusion in dose reconstruction. NIOSH, however, does not consider the following exposures to be occupationally derived:

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

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

3.1.2 Scope

The NIOSH Dose Reconstruction Project requires assessment of doses from medical X-rays that were required for screening and as a condition of employment. The Paducah Gaseous Diffusion Plant (PGDP) occupational medicine program required preemployment and periodic screening chest X-ray examinations (Turner 2003). The examinations consisted of one posterior-anterior (PA) and one lateral (LAT) chest projection (Turner 2003). In addition to parts of the body exposed in the primary beam of an X-ray machine, other tissues receive some dose from secondary radiation. Secondary radiation consists of X-rays that are scattered from surrounding materials or that escape from the source assembly (Selman 1993). This TBD contains tables that list estimated dose equivalents that are favorable to claimants to organs of the body that result from single and combined PA and LAT chest X-rays for male and female PGDP employees. The tables are the result of an assessment of the air kerma at the source-to-skin distance (SSD), based on specific operating parameters for the facility insofar as these are known.

Attributions and annotations, indicated by bracketed callouts and used to identify the source, justification, or clarification of the associated information, are presented in Section 3.7.

3.2 EXAMINATION FREQUENCIES

Each X-ray examination consisted of one PA and one LAT chest projection. Table 3-1 lists the minimum criteria for examination frequencies for PGDP employees (Turner 2003). This policy has been in place since before 1974, with the exception of the criterion for asbestos workers, which started in about 1986 (Turner 2003).

Table 3-1. Frequency of chest X-ray examinations.

Employees	Frequency
Nonsmokers[a]	Every 5 yr
Smokers under age 40	Every 5 yr
Smokers age 40 and older	Every 3 yr
Asbestos workers[b]	Every 2 yr

a. Ex-smokers are considered smokers for 10 yr after quitting.
b. Program started about 1986.

Regular repeat/retake analyses for the X-ray department have been performed for a number of years. The actual repeat rate is not known. There is no indication that the repeat rate has been of any significance (Turner 2003). There is no evidence that PGDP ever used photofluorography for required chest X-ray examinations (Turner 2003).

3.3 EQUIPMENT AND TECHNIQUES

Table 3-2 lists the medical X-ray equipment used at PGDP during specified periods. A General Electric (GE) machine was used from the opening of the plant in 1952 through February 1975 (Turner 2003). It was replaced by a Picker unit, which served from March 1975 through December 1995 (Turner 2003). The present equipment has been in operation since January 1996 (Turner 2003). Quality assurance has been verified regularly by the Food and Drug Administration and the Commonwealth of Kentucky, as well as by in-house surveys (Turner 2003). The same technician has operated the X-ray unit at PGDP from November 1974 to the present. Interviews with him and with a resident X-ray physicist (Gregory 2003) provided much of the information in this TBD.

Table 3-2. PGDP X-ray equipment.

Period	Equipment
1952–Feb. 1975	GE, some filtration, manual collimator, stationary grid, no phototiming, hand-developed film
Mar. 1975–Dec. 1995	Picker, filtration, automatic collimator, Bucky grid, DuPont cassettes and screen, phototiming, automatic film development
Jan. 1996–present	XMA Linear II Eureka, filtration, automatic collimator, Bucky grid, phototiming, automatic film development

The dose received from an X-ray exposure depends on a number of factors. These include filtration, collimation, use of grids, projection, and size and positioning of the subject. Machine settings determine the peak voltage (applied kilovoltage), current (milliamperes), and exposure time, which can be selected for optimum imaging with minimum dose (Selman 1993). The two most recent machines (see Table 3-2) controlled exposures by phototiming. This permits accurate termination of the exposure when the film has received a predetermined amount of radiation for a properly exposed radiograph. Timing for the GE machine was determined by using standard charts and considering worker size (Turner 2003).

Table 3-3 lists nominal operating parameters for the three machines, all of which are single-phase, for PA and LAT projections. The GE equipment operated in the range from 70 to 90 kVp and the newer machines in the range from 90 to 100 kVp. All used a current of 300 mA (Turner 2003). From March 1975 to the present, the dose with either of the two more recent machines has been comparable for a given procedure. Therefore, organ dose equivalents are determined for two periods: 1952 to February 1975 and March 1975 to the present [1].

Table 3-3. Operating parameters.

Period	Projection	kVp (V)	Current (mA)
1952–Feb. 1975	PA	70–90	300
	LAT	70–90	300
Mar. 1975–Dec. 1995	PA	90–100	300
	LAT	90–100	300
Jan. 1996–present	PA	90–100	300
	LAT	90–100	300

Other factors being equal, the air kerma and resultant organ doses are proportional to the time-integrated current (milliampere-seconds, or mAs) (Selman 1993). Some measurements of mAs were conducted with the present equipment for PA and LAT projections of 16 males and 4 females with body sizes classified as “large,” “medium,” and “small” (Turner 2003). Table 3-4 summarizes the results, listing average values of mAs in each classification and for all 20 persons in the sample. Although the number of subjects is small, both genders exhibit the trend toward larger mAs with increasing body size. Larger values for males are evident. The kerma estimation in Section 3.4 uses the average for the 10 medium male workers from Table 3-4 for all employees [2]. Rounded off, these values for the PA and LAT projections, respectively, are:

$$Q_{PA} = 16 \text{ mAs} \quad \text{and} \quad Q_{LAT} = 64 \text{ mAs} \tag{3-1}$$

Table 3-4. Average mAs for exposures of workers of different body size.

Body size (number of males, females)	Projection	Males (mAs)	Females (mAs)
Large (3 males, 0 females)	PA	26.9	-
	LAT	145	-
Medium (10 males, 2 females)	PA	15.9	14.3
	LAT	64.4	47.5
Small (3 males, 2 females)	PA	10.3	6.2
	LAT	61.8	19.9
All persons (16 males, 4 females)	PA	17.7	10.3
	LAT	79	33.7

3.4 ORGAN DOSE CALCULATIONS

The calculation proceeds in two steps: determination of the air kerma at the entrance to the skin, and conversion of this quantity to dose equivalent in different organs. NCRP (1989, Table B.3, p. 99) lists values of the air kerma (more precisely, the air kerma in air) per mAs at different distances from the source (X-ray focal point) and for different kVp values with a total filtration equivalent to 2.5 mm Al. As stated in Section 3.3, doses for the two more recent PGDP X-ray machines are comparable. Section 3.4.1 determines the air kerma at skin entrance, applicable to both machines from March 1975 to the present, by using Table B.3 from NCRP (1989). Section 3.4.2 assesses the air kerma for the GE equipment, applicable from 1952 to March 1975, by other means. For both periods, this assessment used dose conversion factors from International Commission on Radiological Protection (ICRP) Publication 34 (ICRP 1983) in Sections 3.4.3 and 3.4.4 to evaluate the dose equivalent in various organs.

3.4.1 Air Kerma for Exposures from March 1975 to Present

With an average tube potential of 95 kVp, consistent with Table 3-3, one obtains directly by linear interpolation from Table B.3 of NCRP (1989) (total filtration equivalent to 2.5 mm Al) the air kerma value K_o = 0.19 cGy/(100 mAs) for single-phase generators at a source-to-image distance (SID) r_o = 183 cm (72 in.). It will be convenient to work with the following units:

$$K_o = \frac{0.19\,\text{cGy}}{100\,\text{mAs}} \times \frac{1\,\text{rad}}{\text{cGy}} = \frac{1.9\times10^{-3}\ \text{rad}}{\text{mAs}} \tag{3-2}$$

For an exposure made with Q mAs, the kerma at distance r is given by:

$$K(Q,r) = K_o \left(\frac{r_o}{r}\right)^2 Q\ \text{rad} \tag{3-3}$$

The square of the distance ratio adjusts for the inverse-square dependence of the kerma over the range of distances considered.

For the PA projection, an allowance of 5 cm is made for cassette thickness and 26 cm for chest thickness between the source and image (ORAUT 2005). Therefore, the SSD is r_{PA} = 183 – 31 = 152

cm. For the LAT projection with an assumed chest thickness of 34 cm, r_{LAT} = 183 – 39 = 144 cm (ORAUT 2005). Thus:

$$r_{PA} = 152 \text{ cm} \quad \text{and} \quad r_{LAT} = 144 \text{ cm} \tag{3-4}$$

With r_o = 183 cm, one obtains from equations 3-2 and 3-3 the following values for the kerma at skin entrance for the two projections:

$$K_{PA} = \frac{1.9 \times 10^{-3} \text{ rad}}{\text{mAs}} \left(\frac{183}{152}\right)^2 (16 \text{ mAs}) = 0.044 \text{ rad} \tag{3-5}$$

and

$$K_{LAT} = \frac{1.9 \times 10^{-3} \text{ rad}}{\text{mAs}} \left(\frac{183}{144}\right)^2 (64 \text{ mAs}) = 0.2 \text{ rad} \tag{3-6}$$

These estimates of air kerma at skin entrance apply to exposures made from March 1975 to the present.

The kerma estimate (equation 3-5) for the PA projection can be compared directly to measurements made during an in-house radiation safety survey of the PGDP X-ray facility in June 2003 (Gregory 2003). The exposure measured in the beam at a distance of 183 cm was 19 mR. The value of the kerma at this distance implied by equation 3-5 is 30 mrad, which is consistent with an exposure close to 30 mR, approximately 1.5 times larger than the measured value. Using NCRP (1989) with a total filtration of 3.8 mm Al leads to the calculated kerma value of 0.019 rad at 183 cm. Thus, the estimate (equation 3-5) is probably higher than the actual value by about 50% due to greater filtration than that assumed. However, as applied to PA projections for all persons in this TBD, K_{PA} = 0.044 rad, which is favorable to claimants, is used.

3.4.2 Air Kerma for Exposures from 1952 through February 1975

Detailed information and technical data for operation of the original X-ray installation at PGDP are limited [3]. The latest revision of ORAUT (2005) contains default values for skin-entrance kerma for use in such instances. These take into account common practices of the day, limited filtration and collimation, low applied kilovoltage, slow film speeds, and worker dose studies reported in the literature. With conservative assumptions, the default values probably were approached only rarely in an actual exposure. This TBD uses the default kerma values of ORAUT (2005) for pre-1970 conditions. They are listed in Table 3-5, together with the values given by equations 3-5 and 3-6.

Table 3-5. Air kerma at skin entrance for PA and LAT projections.

Dates	Kerma (rad)	
	PA	LAT
1952–Feb. 1975	0.20	0.50
Mar. 1975–present	0.044	0.20

3.4.3 Dose Equivalents per Exposure for Organs Included in ICRP Publication 34

Tables A2 through A9 in ICRP (1983) list average values of absorbed doses in seven selected organs and the total body per unit entrance kerma (i.e., air kerma in air with no backscatter). For example, the dose equivalent to the active bone marrow is computed for the values of the kerma in Table 3-5.

ICRP (1983, Table A8, p. 59) lists absorbed dose values for active bone marrow for different beam qualities, expressed as the half-value layer (HVL) in millimeters of aluminum. Values that are favorable to claimants, 2.5 mm Al for 1952 to February 1975 (ORAUT 2005) and 3.5 mm Al for March 1975 to the present, are assumed [4]. With a quality factor of unity for X-rays, the values in the ICRP (1983) tables, listed in milligray (organ absorbed dose) per gray (entrance kerma), are numerically equal to millirem of organ dose equivalent per rad of entrance kerma. It follows, therefore, that multiplication of the kerma in rad from Table 3-5 by the values in the ICRP (1983) tables yields the organ dose equivalents *H* in millirem directly. In other words:

$$K(rad) \times ICRP\ value = H(mrem) \qquad (3\text{-}7)$$

With an SID of 183 cm and the two assumed beam qualities, one obtains from Table A8 of ICRP (1983) the values needed to compute the organ dose equivalents for male and female PA and LAT chest projections. With the entrance kerma from Table 3-5, the following summarizes the dose equivalent to the active bone marrow for the four cases:

1952 to February 1975:

PA: 0.20 × 92 = 18 mrem (males) LAT: 0.50 × 37 = 19 mrem (males)
0.20 × 86 = 17 mrem (females) 0.50 × 29 = 15 mrem (females)

March 1975 to present:

PA: 0.044 × 146 = 6.4 mrem (males) LAT: 0.20 × 61 = 12 mrem (males)
0.044 × 141 = 6.2 mrem (females) 0.20 × 48 = 9.6 mrem (females)

For 1952 to February 1975, these dose equivalents agree with the values in ORAUT (2005). These are the first entries in Table 3-6. In principle, the rest of the table values are calculated in similar fashion. However, ICRP (1983) applies to collimated beams, and thus would probably underestimate doses to some organs for 1952 to February 1975. Some organs not in the chest cavity, such as the ovaries, testes, thyroid, and uterus, could be exposed to the primary beam if the collimation is poor. For 1952 to February 1975, the dose conversion factors of ORAUT (2005) for pre-1970 are used.

Table 3-6. Dose equivalent per PA and per LAT exposure for organs included in ICRP Publication 34.

	Dose equivalent (rem)[a]			
	1952–February 1975		**March 1975–present**	
Organ	**PA**	**LAT**	**PA**	**LAT**
Bone marrow (active)	1.8E-02 (m) 1.7E-02 (f)	1.9E-02 (m) 1.5E-02 (f)	6.4E-03 (m) 6.2E-03 (f)	1.2E-02 (m) 9.6E-03 (f)
Breast (female)	9.8E-03	1.3E-01	4.0E-03	6.3E-02
Lungs	8.4E-02 (m) 9.0E-02 (f)	9.7E-02 (m) 1.1E-01 (f)	2.5E-02 (m) 2.7E-02 (f)	5.5E-02 (m) 6.2E-02 (f)
Ovaries	2.5E-02	1.3E-02	1.4E-04	3.2E-04
Testes	5.0E-03	2.5E-03	4.0E-07	2.0E-05
Thyroid	3.5E-02	6.9E-02	2.7E-03	3.0E-02
Uterus (embryo)	2.5E-02	1.3E-02	1.3E-04	2.8E-04

a. (m) = male; (f) = female

3.4.4 Dose Equivalents per Exposure for Organs Not Included in ICRP Publication 34

For estimating dose equivalents with the Interactive RadioEpidemiological Program (IREP), organs not included in ICRP 34 are classified in three anatomical regions, as prescribed by ORAU (2005) and listed in the first column of Table 3-7. In the second column, a single organ from ICRP (1983) is selected from Table 3-6 as representative of the dose to all organs in that region. Column 3 of Table 3-7 lists other organs according to the region in which they are located. With the exception of skin in

the last row, they are assigned the dose equivalent from Table 3-6 for the organ listed in column 2. For the lungs, the slightly larger values for females from Table 3-6 are used for both sexes. The ICRP "remainder organs" (ICRP 1991) are assigned to the group with the largest dose equivalent (thorax).

Table 3-7. Dose equivalent per PA and per LAT exposure for organs not in ICRP Publication 34.

Anatomical region	ICRP 34 organ	Other organs	Dose equivalent (rem)			
			1952–Feb. 1975		March 1975–present	
			PA	LAT	PA	LAT
Thorax	Lungs	Bone surface Esophagus Liver/gall bladder/spleen Remainder organs Stomach Thymus	9.0E-02	1.1E-01	2.7E-02	6.2E-02
Abdomen	Ovaries	Colon/rectum Urinary/bladder	2.5E-02	1.3E-02	1.4E-04	3.2E-04
Head/neck	Thyroid	Eye/brain Skin	6.4E-03 2.7E-01	6.9E-02 6.8E-01	2.7E-03 6.2E-02	3.0E-02 2.8E-01

The skin is the only organ listed in Table 3-7 that does not involve ICRP (1983) dose conversion factors. The estimated dose equivalent is numerically equal to the product of the entrance kerma (Table 3-5) and a backscatter factor based on Table B.8 of NCRP (1989). For the period 1952 to February 1975, the default pre-1970 skin doses from ORAUT (2005) are assigned in Table 3-7. The values for March 1975 to present are obtained from Table 3-5 with a backscatter factor of 1.4 based on Table B-8 of NCRP (1989).

3.4.5 Combined Dose Equivalents for PA and LAT Exposures

The periodic X-ray examinations at PGDP consisted of one PA and one LAT exposure (Turner 2003). Table 3-8 lists the estimated resultant total organ dose equivalents per examination. With the exception of the skin (last row), these values are the sums of the respective dose equivalents from Tables 3-6 and 3-7. If two sets of values, (m) and (f), are listed in Table 3-6, the larger of the respective sums was entered in Table 3-8. For skin, two estimates were made for consideration in each period for Table 3-8 as follows: From March 1975 to the present, when both PA and LAT projections were made, the posterior skin (Table 3-7) received a dose equivalent of 6.2×10^{-2} rem (with backscatter) from the PA projection plus radiation from the LAT projection (without backscatter) [5]. The latter component of the posterior skin dose equivalent is roughly approximated by the LAT lung dose equivalent, which from Table 3-7 is 6.2×10^{-2} rem. This estimate gives a total dose equivalent of $6.2 \times 10^{-2} + 6.2 \times 10^{-2} = 1.2 \times 10^{-1}$ rem for the posterior skin when both projections are made.

3.5 UNCERTAINTY

For 1952 to February 1975, the values listed in Tables 3-6 and 3-7 are based on assumptions favorable to claimants described by ORAUT (2005). For further conservatism, the authors suggest the use of a positive error of +30%.

Table 3-8. Organ dose equivalents for combined PA and LAT examinations.

Organ	Dose equivalent (rem)	
	1952–Feb. 1975	Mar. 1975–present
Bone marrow (active)	3.7E-02	1.8E-02
Bone surface	2.0E-01	8.9E-02
Breast (female)	1.4E-01	6.7E-02
Colon/rectum	3.8E-02	4.6E-04
Esophagus	2.0E-01	8.9E-02
Eye/brain	7.5E-02	3.3E-02
Liver/gall bladder	2.0E-01	8.9E-02
Lungs	2.0E-01	8.9E-02
Ovaries	3.8E-02	4.6E-04
Remainder	2.0E-01	8.9E-02
Stomach	2.0E-01	8.9E-02
Testes	7.5E-03	2.0E-05
Thymus	2.0E-01	8.9E-02
Thyroid	1.0E-01	3.3E-02
Urinary/bladder	3.8E-02	4.6E-04
Uterus (embryo)	3.8E-02	4.1E-04
Skin	(a)	(a)

a. Summing the skin doses is not appropriate since different areas of skin are exposed for each of these projections

For March 1975 to the present, Table 3-9 lists sources of uncertainty in worker organ dose equivalents. The first column lists, from top to bottom, the sequential steps by which the values in Tables 3-6 and 3-7 were obtained. The second column characterizes the potential significance of these values in terms of uncertainties they might introduce. Knowledge of actual organ dose equivalents for a given procedure is uncertain because of physical factors and variations between individuals.

Table 3-9. Potential sources of uncertainty in organ dose equivalent assessments.

Source	Assessment
Equipment and techniques, Section 3.3	GE machine (1952–February 1975): little documentation. Use conservative default values (ORAUT 2005). Newer machines (March 1975–present): little uncertainty in knowledge of radiation field, verified by independent surveys. Use technique factors.
NCRP (1989), Section 3.4	Table B.3 of NCRP (1989) lists air kerma per mAs at different distances for various kVp and filtration from measurements of Zamenhof, Shahabi, and Morgan (1987), which states average accuracy of 0.3% for fit to measurements and 10% for worker-dose validation.
Air kerma *K* at skin entrance, equation 3-3, Table 3-5	K_o determined by tube voltage and *Q* by current and time with relatively little error. Distance *r* from source to skin subject to considerable variation because of worker size and placement. Analysis (Attachment A) indicates net uncertainty in *K* due to these factors by perhaps as much as 35%.
ICRP (1983), Table 3-6 for ICRP 34 organs, Table 3-7 for other organs	ICRP 34 tables for organ absorbed doses per unit entrance kerma are derived from Monte Carlo calculations for anthropomorphic phantom (Gorson, Lassen, and Rosenstein 1982). Additional uncertainties in actual organ dose equivalents introduced in this step include differences between mathematical model and actual organs and individual anatomical variations among persons. Rough estimate of uncertainty, 50%.

As summarized in the first row of Table 3-9, organ dose equivalent estimations for the original PGDP X-ray machine (before March 1975) are upper limits, based on knowledge of machines and practices

of the time. Much better characterization of the radiation field is known for the two later machines. In the second row, the physical data in NCRP (1989) have been shown to have little error. The assessment of 10% accuracy for worker dose (Zamenhof, Shahabi, and Morgan 1987) could reflect variations among workers.

With other conditions fixed, uncertainties in the peak voltage, tube current and exposure time, and placement of the individual in the X-ray beam contribute to uncertainty in the kerma at skin entrance (Table 3-9, third row). Based on NCRP (1989), the kerma was calculated from equation 3-3. By assigning values for uncertainties as coefficients of variation (ratio of the standard deviation and mean) for *r*, *Q,* and the tube potential, one can apply error-propagation formalism to estimate the resultant coefficient of variation for the kerma. Attachment A describes this procedure. For uncertainties of 10% in *r* and 5% in *Q* and the voltage, it is suggested that K_{PA} = 0.044 ±0.015 rad at the 95% confidence level. The estimated uncertainty in the kerma values at skin entrance for March 1975 to the present (last row in Table 3-5) is no more than 35%, attributable primarily to differences among workers and their placement.

In the last row of Table 3-9, the same conversion factors from entrance kerma to organ doses are used for all individuals, a distinction being made between male and female for some organs. In any case, the conversion factors are representative for an exposed individual (for the assumed kerma) to

the extent that the anatomical features of the individual match those of the phantom, which are the basis for the tables. The variation introduced in this step is not known. An indication can be gained through comparison with dose conversion factors in ICRP (1983) for the 5-yr-old pediatric phantom under the same irradiation conditions. Doses in the smaller phantom per unit entrance kerma are often larger by factors approaching 2. Estimated uncertainty due to adult worker variability might be as large as 50%.

In summary, there is relatively little uncertainty associated with the first two steps in Table 3-9. The third and fourth steps entail, sequentially, estimated uncertainties of 35% and 50%. In the worst case, these would act fully in the same direction to increase the error. An exposure could then give a dose equivalent for some individuals that is larger than those listed in Tables 3-6 and 3-7 for March 1975 to the present by the factor 1(1.35)(1.50) = 2. Uncertainty in the values of the dose equivalent for this period in Table 3-8 is, conservatively, not more than a factor of 2.

3.6 DOSE RECONSTRUCTION

3.6.1 Organ Dose Equivalents Favorable to Claimants per Examination

The normal occupational chest X-ray examination at PGDP consisted of a single PA and a single LAT exposure. Table 3-10 lists estimates that are favorable to claimants, allowing for uncertainty, of organ dose equivalents per examination that dose reconstructors can use. The total dose equivalent to an organ of a worker is the product of the value in Table 3-10 and the number of examinations the worker underwent during each period, including a preemployment examination. Table 3-1 lists the minimum frequency of chest X-ray examinations. Attachment A provides dose equivalents for lumbar spine examinations (possible in the early days).

The values in Table 3-10 for 1952 to February 1975 are 1.3 times the values in Table 3-8. They reflect the +30% error favorable to claimants assessed by ORAUT (2005), as stated in Section 3.5. Dose equivalents for March 1975 to the present are twice the estimated values in Table 3-8. This factor reflects the estimate of uncertainty favorable to claimants described in Section 3.5.

Table 3-10. Organ dose equivalents favorable to claimants per examination consisting of one PA and one LAT exposure.

Organ	Dose equivalent (rem)	
	1952–Feb. 1975	Mar. 1975–present
Bone marrow (active)	4.8E-02	3.6E-02
Bone surface	2.6E-01	1.8E-01
Breast (female)	1.8E-01	1.3E-01
Colon/rectum	4.9E-02	9.2E-04
Esophagus	2.6E-01	1.8E-01
Eye/brain	9.8E-02	6.6E-02
Liver/gall bladder/spleen	2.6E-01	1.8E-01
Lungs	2.6E-01	1.8E-01
Ovaries	4.9E-02	9.2E-04
Remainder	2.6E-01	1.8E-01
Stomach	2.6E-01	1.8E-01
Testes	9.8E-03	4.0E-05
Thymus	2.6E-01	1.8E-01
Thyroid	1.3E-01	6.6E-02
Urinary/bladder	4.9E-02	9.2E-04
Uterus	4.9E-02	8.2E-04
Skin	(a)	(a)

a. Summing the skin doses is not appropriate since different areas of skin are exposed for each of these projections

3.6.2 Optional Initial Screening

It is sometimes useful to establish initially if a given exposure history indicates that the levels warrant precise evaluation. Table 3-11 divides organs into groups. Each organ in a group has a dose equivalent that is no smaller than its value in Table 3-10.

Table 3-11. Upper-bound organ dose equivalents per examination for screening.

Organ	Dose equivalent (rem)	
	1952–Feb. 1975	Mar. 1975–present
Colon/rectum, ovaries, testes, urinary/bladder, uterus	4.9E-02	9.2E-04
Bone marrow (active), eye/brain, thyroid	1.3E-01	6.6E-02
Bone surface, breast (female), esophagus, liver/gall bladder/spleen, lungs, remainder, stomach, thymus	2.6E-01	1.8E-01
Skin	1.0E-00	6.2E1E-01

Therefore, dose reconstructors can use Table 3-11 to estimate an upper bound favorable to claimants for an organ dose equivalent per examination. Unless the records indicate more frequent X-rays, base the expected number of examinations on Table 3-1. Assume a preemployment examination followed by a regular examination every 3 yr thereafter, whether the worker was a smoker or not, until 1986. Beginning at the start of 1986, assume that the examination frequency changes to every 2 yr to be favorable to claimants.

Example. Calculate an upper bound for the dose equivalent to the active bone marrow of a worker. The individual was hired on February 1, 1962, and worked steadily until retirement on March 31, 1996. Determine the number of examinations during each of the two periods and apply Table 3-11. Without making a distinction for smoking, assume initially an examination every 3 yr around February 1. The length of employment was 34 yr and 2 months. Starting with the preemployment examination, there would be a total of five examinations with the older GE equipment (the preemployment examination plus those in 1965, 1968, 1971, and 1974). Examinations after February 1974 were with the more recent equipment [four through 1986 (every 3 yr) and five from 1988 through

1996 (every 2 yr) for a total of nine]. An upper bound for the dose equivalent to the active bone marrow, based on Table 3-11, is:

$$5 \times (1.3 \times 10^{-1}) + 9 \times (6.6 \times 10^{-2}) = 1.5 \text{ rem} \quad (3\text{-}8)$$

3.7 ATTRIBUTIONS AND ANNOTATIONS

Where appropriate in this document, bracketed callouts have been inserted to indicate information, conclusions, and recommendations provided to assist in the process of worker dose reconstruction. These callouts are listed here in the Attributions and Annotations section, with information to identify the source and justification for each associated item. Conventional References, which are provided in the next section of this document, link data, quotations, and other information to documents available for review on the Project's Site Research Database.

[1] Turner, James E. ORAU Team. Consultant to Integrated Environmental Management, Inc. 2003.
The decision to develop one set of organ doses for the 1975 to present time period is based on the fact that the pre-selectable technique factors for the two different machines used during this time period are identical.

[2] Turner, James E. ORAU Team. Consultant to Integrated Environmental Management, Inc. 2003. The dose conversion factors in ICRP 34 are based on an average chest thickness of about 23 cm. This was interpreted to mean "medium" size.

[3] Turner, James E. ORAU Team. Consultant to Integrated Environmental Management, Inc. 2003.
The information about the X-ray machine used from 1952-1975 is limited to the brand of machine, and operating voltage range.

[4] Turner, James E. ORAU Team. Consultant to Integrated Environmental Management, Inc. 2003. ORAU 2005 describes how 2.5 mm Al eq. filtration is favorable to claimants for early time periods, and 3.5 mm Al eq. for the later time period is favorable to claimants because the DCFs are higher for an HVL of 3.5 than 2.5, even though the entrance kerma is based on an HVL of 2.5 mm Al eq.

[5] Turner, James E. ORAU Team. Consultant to Integrated Environmental Management, Inc. 2003. For the posterior skin, the backscatter factor from the LAT projection should not be applied as the beam is tangential to the posterior skin.

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GLOSSARY

absorbed dose
Energy absorbed per unit mass; units are rad and gray (Gy).

backscatter (radiation)
Radiation that is scattered backwards, enhancing skin dose where an X-ray beam normally enters the body.

dose equivalent
Product of absorbed dose and quality factor or radiation weighting factor. With dose in rad, unit is rem; with dose in Gy, unit is sievert (Sv).

gray (Gy)
Unit of absorbed dose (1 Gy = 1 J/kg = 100 rad).

kerma
Sum of initial kinetic energies of all charged particles (including Auger electrons) liberated by uncharged radiation per unit mass. Units are rad and Gy.

primary X-rays
X-rays that constitute the useful beam that emerges from the tube target.

rad
Unit of absorbed dose (1 rad = 100 erg/g = 0.01 Gy).

rem
Unit of dose equivalent.

secondary radiation
As distinct from primary X radiation, secondary radiation consists of X-rays that have been scattered from objects or that leak from the source assembly.

sievert (Sv)
Unit of dose equivalent.

X-ray
Ionizing electromagnetic radiation of non-nuclear origin; also, a radiograph.

ATTACHMENT A
ERROR PROPAGATION FOR KERMA
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The kerma at skin entrance distance for the two newer machines used from March 1975 to the present (Table 3-5) is calculated from equation 3-3. Given values for uncertainties in *r*, *Q*, and the tube potential, a standard formalism for error propagation (Taylor 1997; Tsoulfanidis 1983) can be applied to estimate the uncertainty in *K* that results. Because the beam intensity is approximately proportional to the 1.7 power of the tube potential *V*, one can make the replacement:

$$K_o = C_o V^{1.7} \tag{B-1}$$

where C_o is the constant of proportionality in equation 3-3. To show the explicit dependence of the kerma on these quantities, one can then write in place of equation 3-3:

$$K(V,r,Q) = C_o V^{1.7} \left(\frac{r_o}{r} \right)^2 Q \tag{B-2}$$

For the analysis, it is convenient to employ uniform notation for the variables, defined by writing:

$V = X_1$	with mean $\mu_1 = \mu_V$	and	standard deviation	$\sigma_1 = \sigma_V$
$r = X_2$	with mean $\mu_2 = \mu_r$	and	standard deviation	$\sigma_2 = \sigma_r$
$Q = X_3$	with mean $\mu_3 = \mu_Q$	and	standard deviation	$\sigma_3 = \sigma_Q$

The kerma can be written:

$$K(X_1, X_2, X_3) = C_o r_o^2 \frac{X_1^{1.7} X_3}{X_2^2} \tag{B-3}$$

Given estimated uncertainties σ_i in the X_i, the task is to estimate the resulting uncertainty σ_K in *K*.

According to the formalism, one approximates the kerma (equation B-3) by making a Taylor series expansion about the point $\mu = (\mu_1, \mu_2, \mu_3)$ and retaining only the linear terms. The variables are assumed to be independent. It follows that:

$$\sigma_K^2 \cong \sum_{i=1}^{3} \left(\frac{\partial K}{\partial X_i} \right)_{\mu}^2 \sigma_i^2 \tag{B-4}$$

ATTACHMENT A
ERROR PROPAGATION FOR KERMA

The partial derivatives are to be evaluated at the point μ. Carrying out the differentiations from equation B-3 and substituting into equation B-4 gives:

$$\sigma_K^2 \cong \left(C_o r_o^2\right)^2 \left[\left(\frac{1.7 \mu_1^{0.7} \mu_3}{\mu_2^2} \right)^2 \sigma_1^2 + \left(\frac{-2 \mu_1^{1.7} \mu_3}{\mu_2^3} \right)^2 \sigma_2^2 + \left(\frac{\mu_1^{1.7}}{\mu_2^2} \right)^2 \sigma_3^2 \right] \tag{B-5}$$

$$\cong \left(C_o r_o^2 \frac{\mu_1^{1.7} \mu_3}{\mu_2^2} \right)^2 \left[2.89 \left(\frac{\sigma_1}{\mu_1} \right)^2 + 4 \left(\frac{\sigma_2}{\mu_2} \right)^2 + \left(\frac{\sigma_3}{\mu_3} \right)^2 \right]$$

Comparison of the factor outside the bracket with equations B-2 and B-3 shows that it is the square of the kerma $K(\mu)$ at point μ. Returning to the original notation with K_o, r, and Q, one can write in place of the last equation:

$$\frac{\sigma_K}{K(\mu)} \cong \left[2.89 \left(\frac{\sigma_V}{\mu_V} \right)^2 + 4 \left(\frac{\sigma_r}{\mu_r} \right)^2 + \left(\frac{\sigma_Q}{\mu_Q} \right)^2 \right]^{\frac{1}{2}} \tag{B-6}$$

The ratio of the standard deviation (standard error) and the mean is called the *coefficient of variation*, which for the kerma can be denoted by $c_K = \sigma_K \div \mu_K$. With similar notation for the coefficients of variation for the other variables, equation B-6 can be written:

$$c_K \cong \sqrt{2.89 c_V^2 + 4 c_r^2 + c_Q^2} \tag{B-7}$$

This result provides an estimate of the uncertainty of the kerma in terms of the uncertainties in V, r, and Q. The approximation is best to the extent that the $\sigma_i << \mu_i$.

Values of the operating parameters used to obtain K_{PA} = 0.044 rad, equation 3-5, can be used as estimates for the quantities needed in equation B-7. For orientation, it will be assumed that the voltage V and mAs Q have standard errors of ±5%. An uncertainty in the SSD r of 10 cm, or ±7% with r = 152 cm, will be assumed to allow for anatomical and placement variations. With $c_V = c_Q = 0.05$ and $c_r = 0.07$, equation B-7 gives $c_K \cong 0.17$. Thus, the estimated standard error of the PA kerma is 0.17 × 0.044 = 0.007 rad. With assumed normal statistics, K_{PA} = 0.044 ±0.015 rad at the 95% confidence level (1.96σ). That is to say, the probability is 0.95 that the true value of the kerma (which is unknown) is in the stated range. The interval width is ±34%. With other reasonable assumptions, it appears that the largest contributor to uncertainty in row 3 of Table 3-9 rises from variations in the SSD. Use of Tables 3-6 and 3-7 implies that r = 152 cm for all persons. The uncertainty in the kerma at skin entrance is assumed to be no greater than about 35%.