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RECORD OF ISSUE/REVISIONS

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Draft	11/17/2003	00-A	New technical basis document for the Paducah Gaseous Diffusion Plant – Occupational Medical Dose. Initiated by Jay J. Maisler.
Draft	12/09/2003	00-B	Incorporates OCAS comments. Initiated by Jay J. Maisler.
Draft	12/29/2003	00-C	Incorporates revisions for consistency with ORAUT-TIB-0006 draft revision and responses to additional internal comments. Initiated by Jay J. Maisler.
02/05/2004	02/05/2004	00	First approved issue. Initiated by Jay J. Maisler.

ACRONYMS AND ABBREVIATIONS

Al	aluminum
AP	anterior-posterior (X-ray view)
cm	centimeter
GE	General Electric Corporation
Gy	gray
HVL	half-value layer
ICRP	International Commission on Radiological Protection
IREP	Interactive RadioEpidemiological Program
kerma	Kinetic Energy Released per unit MAss (see Glossary)
kVp	peak voltage (kilovolts)
LAT	lateral (X-ray view)
mA	milliampere
mAs	milliampere second
mGy	milligray
mm	millimeter
mR	milliroentgen
mrad	millirad
mrem	millirem
NCRP	National Council on Radiation Protection and Measurements
NIOSH	National Institute for Occupational Safety and Health
PA	posterior-anterior (X-ray view)
PGDP	Paducah Gaseous Diffusion Plant
QA	quality assurance
SID	source-to-image distance
SSD	source-to-skin distance
TBD	technical basis document

3.0 OCCUPATIONAL MEDICAL DOSE

3.1 INTRODUCTION

The National Institute for Occupational Safety and Health (NIOSH) dose reconstruction project requires assessment of doses from medical X-rays that were required as a condition of employment. The Paducah Gaseous Diffusion Plant (PGDP) occupational medicine program required preemployment and regular diagnostic chest X-ray examinations. The examinations consisted of one posterior-anterior (PA) and one lateral (LAT) chest projection. 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. This technical basis document (TBD) includes tables that list claimant-favorable estimated dose equivalents 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 derived from 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.

3.2 EXAMINATION FREQUENCIES

Each X-ray examination consisted of one PA and one LAT chest view. Table 3-1 lists the minimum criteria for examination frequencies for PGDP employees. This policy has been in place since before 1974, with the exception of the criterion for asbestos workers, which started in about 1986. Some lumbar spine projections might have been made in the early days. These are addressed in Attachment 3B.

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

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

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

Regular repeat/retake analyses for the X-ray department have been performed for a number of years. There is no indication that the repeat rate has been of any significance. Occasional X-ray exposures, as for a possible broken bone, are not included in the occupational dose reconstruction because they are not considered a requirement for employment. There is no evidence that fluoroscopy was ever used for required chest X-ray examinations.

3.3 EQUIPMENT AND TECHNIQUES

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

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 a diagnostic X-ray exposure depends on a number of factors. These include filtration, collimation, and the use of grids, as well as the projection and the size and positioning of the subject. Machine settings determine the peak voltage (kVp), current (mA), and exposure time, which can be selected for optimum imaging with minimum dose. With the two most recent machines (see Table 3-2), exposures were controlled by phototiming. This permits accurate termination of the exposure when the subject has received a predetermined amount of radiation needed for a particular radiograph. Timing for the GE machine was determined by using standard charts and taking patient size into account. This might have resulted in more exposure to some patients, and the claimant-favorable dose values used in this TBD take this into account.

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 three used a current of 300 mA. From March 1975 to the present, the dose with either of the two more recent machines listed in Table 3-2 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.

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 (mAs). Some measurements of mAs were conducted with the present equipment for PA and LAT views of 16 males and 4 females with body sizes classified as “large,” “medium,” and “small.” 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, the trend toward larger mAs with increasing body size is seen for both sexes. 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. Rounded off, these values are, respectively, for the PA and LAT views,

$$Q_{\mathrm{PA}} = 16 \text{ mAs} \qquad \text{and} \qquad Q_{\mathrm{LAT}} = 64 \text{ mAs} \ . \qquad (3.3-1)$$

As described at the end of Section 3.4.1, actual measurements (Gregory 2003) indicate that the kerma calculated from these values is about 50% larger than the actual value (claimant-favorable).

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

Body size (number males, females)	View	Males (mAs)	Females (mAs)
Large (3 m, 0 f)	PA	26.9	-
	LAT	145.	-
Medium (10 m, 2 f)	PA	15.9	14.3
	LAT	64.4	47.5
Small (3 m, 2 f)	PA	10.3	6.2
	LAT	61.8	19.9
All persons (16 m, 4 f)	PA	17.7	10.3
	LAT	79.0	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. Table B.3, p. 99, of National Council on Radiation Protection and Measurements (NCRP) Report 102 (NCRP 1989) 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. The discussion in Section 3.4.1 determines the air kerma at skin entrance, applicable to both machines for the period from March 1975 to the present, by using Table B.3 from NCRP (1989). The discussion in Section 3.4.2 assesses the air kerma for the GE equipment, applicable for the period 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 1982) 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:

$$K_o = \frac{0.19 \text{ cGy}}{100 \text{ mAs}} \times 1 \text{ rad cGy}^{-1} = 1.9 \times 10^{-3} \text{ rad (mAs)}^{-1} \quad . \qquad (3.4.1-1)$$

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

$$K(Q, r) = K_o \left(\frac{r_o}{r}\right)^2 Q \quad \text{rad} \quad . \qquad (3.4.1-2)$$

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

For the PA view, an allowance of 5 cm is made for cassette thickness and 26 cm for chest thickness between the source and image. 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. Thus,

$$r_{\text{PA}} = 152 \text{ cm} \qquad \text{and} \qquad r_{\text{LAT}} = 144 \text{ cm} \quad . \tag{3.4.1-3}$$

With r_o = 183 cm, one obtains from equations 3.4.1-1 through 3.4.1-3 the following values for the kerma at skin entrance for the two projections,

$$K_{\text{PA}} = \frac{1.9 \times 10^{-3} \text{ rad}}{\text{mAs}} \left(\frac{183}{152}\right)^2 (16 \text{ mAs}) = 0.044 \text{ rad} \tag{3.4.1-4}$$

and

$$K_{\text{LAT}} = \frac{1.9 \times 10^{-3} \text{ rad}}{\text{mAs}} \left(\frac{183}{144}\right)^2 (64 \text{ mAs}) = 0.20 \text{ rad} \quad . \tag{3.4.1-5}$$

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

The kerma estimate (equation 3.4.1-4) for the PA view 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 3.4.1-4 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 3.4.1-4) is probably higher than the actual value by about 50%, due to greater filtration than that assumed. However, as applied to PA views for all persons in this TBD, K_{PA} = 0.044 rad, which is claimant-favorable, 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. Default values for skin-entrance kerma have been developed for use in such instances by Kathren et al. (2003). These take into account common practices of the day, limited filtration and collimation, low kVp, slow film speeds, and patient dose studies reported in the literature. With conservative assumptions, the default values probably were approached only rarely in an actual exposure. The default kerma values of Kathren et al. (2003) for pre-1970 conditions are used in this TBD. They are listed in Table 3-5, together with the values given by equations 3.4.1-4 and 3.4.1-5.

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

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 (1982) 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.

Absorbed dose values for active bone marrow are listed in Table A8, p. 59, of ICRP (1982) for different beam qualities, expressed as the half-value layer (HVL) in mm Al. Claimant-favorable values, 2.5 mm Al for the time period 1952-Feb. 1975 (Kathren et al. 2003) and 3.5 mm Al for Mar. 1975-present, are assumed. With a quality factor of unity for X-rays, the numbers in the ICRP (1982) tables, listed in mGy (organ absorbed dose) per Gy (entrance kerma), are numerically equal to mrem 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 numbers in the ICRP (1982) tables yields the organ dose equivalents *H* in mrem directly. In other words,

$$K(\text{rad}) \times \text{ICRP Value} = H(\text{mrem}) \quad . \qquad (3.4.3\text{-}1)$$

With an SID of 183 cm and the two assumed beam qualities, one obtains from Table A8 of ICRP (1982) the values needed to compute the organ dose equivalents for (male/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 the period 1952 to February 1975, these dose equivalents agree with the values given by Kathren et al. (2003). These are the first entries in Table 3-6. In principle, the rest of the table is calculated in similar fashion. However, ICRP 34 applies to collimated beams, and would thus likely underestimate the doses to some organs for the earlier period, 1952-Feb. 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-Feb. 1975, the dose conversion factors of Kathren et al. (2003) for pre-1970 are used.

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

Organ	Dose equivalent (mrem)[a]			
	1952–Feb. 1975		Mar. 1975–present	
	PA	LAT	PA	LAT
Bone marrow (active)	18. (m) 17. (f)	19. (m) 15. (f)	6.4 (m) 6.2 (f)	12. (m) 9.6 (f)
Breast (female)	9.8	130.	4.0	63.
Lungs	84. (m) 90. (f)	97. (m) 110. (f)	25. (m) 27. (f)	55. (m) 62. (f)
Ovaries	25.	13.	0.14	0.32
Testes	5.0	2.5	0.0004	0.02
Thyroid	35.	69.	2.7	30.
Uterus (embryo)	25.	13.	0.13	0.28

a. (m) denotes 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) for organs not included in ICRP (1982), these organs are classified in three anatomical regions, as listed in the

first column of Table 3-7. In the second column, a single organ from ICRP (1982) is selected from Table 3-6 as representative of the dose to all organs in that region. Column three lists other body organs according to the region in which they are located. With the exception of the skin in the last row, they are assigned the dose equivalent from Table 3-6 for the organ listed in column two. For the lungs, the slightly larger values for females from Table 3-6 are used for both sexes. The ICRP

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

Anatomical region	ICRP 34 organ	Other organs	Dose equivalent (mrem)			
			1952–Feb. 1975		Mar. 1975–present	
			PA	LAT	PA	LAT
Thorax	Lungs	Bone surface Esophagus Liver/gall bladder/spleen Remainder organs Stomach Thymus	90.	110.	27.	62.
Abdomen	Ovaries	Colon/rectum Urinary/bladder	25.	13.	0.14	0.32
Head/neck	Thyroid	Eye/brain	6.4	69.	2.7	30.
		Skin	270.	680.	140.	340.

“remainder organs” (ICRP 1991) are assigned to the group (thorax) with the largest dose equivalent.

The skin is the only organ listed in Table 3-7 that does not involve ICRP (1982) 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). Kathren et al. (2003) have calculated default skin dose equivalents for pre-1970, 1970-1980, and post 1980. Their pre-1970 values are used in this TBD for the time period 1952 to February 1975 and their 1970-1985 values for the time period March 1975 to present.

3.4.5 Combined Dose Equivalents for PA and LAT Exposures

The regular diagnostic X-ray examinations at PGDP consisted of one PA and one LAT exposure. The estimated resultant total organ dose equivalents per examination are listed in Table 3-8. With the exception of the skin (last row), which does not depend on ICRP (1982), 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), appear in Table 3-6, the larger sum was entered in Table 3-8. For the skin, two estimates were made for consideration in each period for Table 3-8 as follows. During the period from March 1975 to the present, when both PA and LAT views were made, the posterior skin (Table 3-7) received a dose equivalent of 140. mrem (with backscatter) from the PA view plus radiation entailed from the LAT view (without backscatter). The latter component of the posterior skin dose equivalent is roughly approximated by the LAT lung dose equivalent, which from Table 3-7 is 62. mrem. This estimate gives a dose equivalent of 140. + 62. = 200. mrem for the posterior skin when both views are made. Using the same prescription for LAT skin gives a dose equivalent of 340. + 27. = 370. mrem. The claimant-favorable larger estimate was selected for the last row in Table 3-8 for the combined exposure of the skin in the period from March 1975 to the present. A similar computation leads to the value of 770. mrem for the period from 1952 to February 1975.

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

Organ	Dose equivalent (mrem)	
	1952-Feb. 1975	Mar. 1975-present
Bone marrow (active)	37.	18.
Bone surface	200.	89.
Breast (female)	140.	67.
Colon/rectum	38.	0.46
Esophagus	200.	89.
Eye/brain	75.	33.
Liver/gall bladder	200.	89.
Lungs	200.	89.
Ovaries	38.	0.46
Remainder	200.	89.
Stomach	200.	89.
Testes	7.5	0.02
Thymus	200.	89.
Thyroid	100.	33.
Urinary/bladder	38.	0.46
Uterus (embryo)	38.	0.41
Skin	770.	370.

3.5 UNCERTAINTY

For the period from 1952 to February 1975, the values listed in Tables 3-6 and 3-7 are based on claimant-favorable assumptions described by Kathren et al. (2003). For further conservatism, these authors suggest that a positive error of +30% be used.

For the period from March 1975 to the present, sources of uncertainty in patient organ dose equivalents are included in Table 3-9. 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 both physical factors and variations among different individuals.

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 considered 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 patient dose (Zamenhof, Shahabi, and Morgan 1987) could reflect variations among patients.

With other conditions fixed, any uncertainties in the kVp, 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 3.4.1-2. 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. This procedure is described in Attachment 3A. 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 patients and their placement.

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

Source	Assessment
Equipment and techniques; Section 3.3	GE machine (1952-Feb. 1975): little documentation. Use conservative default values (Kathren et al. 2003). Newer machines (Mar.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 patient-dose validation.
Air kerma *K* at skin entrance, eq. 3.4.1-2, 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 patient size and placement. Analysis (Attachment 3A) indicates net uncertainty in *K* due to these factors by perhaps as much as 35%.
ICRP (1982), 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%.

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 on which the tables are based. The variation introduced in this step is not known. An indication can be gained through comparison with dose conversion factors in ICRP (1982) for the 5-year-old pediatric phantom under the same irradiation conditions. Doses in the smaller phantom per unit entrance kerma are often larger by factors approaching two. Roughly, it is estimated that uncertainty due to adult patient 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 the period from March 1975 to the present by the factor 1(1.35)(1.50) = 2. It is estimated conservatively that uncertainty in the values of the dose equivalent for this period in Table 3-8 is not more than a factor of two.

3.6 DOSE RECONSTRUCTION

3.6.1 Claimant-Favorable Organ Dose Equivalents per Examination

The normal occupational chest X-ray examination at PGDP consisted of a single PA and a single LAT exposure. Table 3-10 provides claimant-favorable estimates, allowing for uncertainty, of organ dose equivalents per examination that can be used for dose reconstruction. 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. The minimum frequency of

chest X-ray examinations is listed in Table 3-1. Dose reconstruction for a lumbar spine examination (possible in the early days) is given in Attachment 3B.

Except for skin, which does not depend on ICRP (1982) (see Section 3.4.4), the values in Table 3-10 for the period from 1952 to February 1975 are 1.3 times the values listed in Table 3-8. They thus reflect the claimant-favorable +30% error assessed by Kathren et al. (2003), as stated at the beginning of Section 3.5.. Dose equivalents for the period from March 1975 to the present are twice the estimated values from Table 3-8. This factor reflects the client-favorable estimate of uncertainty described at the end of Section 3.5.

Table 3-10. Claimant-favorable organ dose equivalents per examination consisting of one PA and one LAT exposure.

Organ	Dose equivalent (mrem)	
	1952-Feb. 1975	**Mar. 1975-present**
Bone marrow (active)	48.	36.
Bone surface	260.	180.
Breast (female)	180.	130.
Colon/rectum	49.	0.92
Esophagus	260.	180.
Eye/brain	98.	66.
Liver/gall bladder/spleen	260.	180.
Lungs	260.	180.
Ovaries	49.	0.92
Remainder	260.	180.
Stomach	260.	180.
Testes	9.8	0.04
Thymus	260.	180.
Thyroid	130.	66.
Urinary/bladder	49.	0.92
Uterus	49.	0.82
Skin	770.	370.

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. In Table 3-11, organs other than skin have been divided into three groups. Each organ in a group has been assigned 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 (mrem)	
	1952-Feb. 1975	**Mar. 1975-present**
Colon/rectum, ovaries, testes, urinary/bladder, uterus	49.	0.92
Bone marrow (active), eye/brain, thyroid	180.	66.
Bone surface, breast (female), esophagus, liver/gall bladder/ spleen, lungs, remainder, stomach, thymus	260.	180.
Skin	770.	370.

Therefore, the shorter Table 3-11 can be used to estimate a claimant-favorable upper bound for an organ dose equivalent per examination. Unless the records indicate that more frequent X rays were provided, the expected number of examinations can be based on Table 3-1. Assume a preemployment examination, followed by a regular examination every 3 years 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 years to be claimant-favorable.

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 years around February 1. The length of employment was 34 years and 2 months. Starting with the preemployment examination, there would be a total of five made with the older GE equipment: the preemployment examination plus those in 1965, 1968, 1971, and 1974. Those after February 1974 were with the more recent equipment. Four were made through 1986 (every 3 years) and five from 1988 through 1996 (every 2 years), for a total of nine with the more recent equipment. An upper bound for the dose equivalent to the active bone marrow, based on Table 3-11, is

$$5 \times 180. + 9 \times 66. = 1500. \text{ mrem.}$$

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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^{-1} = 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^{-1} = 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 3A
ERROR PROPAGATION FOR KERMA

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 3.4.1-2. 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,

$$K_o = C_o V^{1.7} , \qquad \text{(A - 1)}$$

where C_o is the constant of proportionality, in equation 3.4.1-2. To show the explicit dependence of the kerma on these quantities, one can then write in place of equation 3.4.1-2,

$$K(V,r,Q) = C_o V^{1.7} \left(\frac{r_o}{r}\right)^2 Q \quad . \qquad \text{(A – 2)}$$

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

$$K(X_1, X_2, X_3) = C_o r_o^2 \frac{X_1^{1.7} X_3}{X_2^2} \quad . \qquad \text{(A – 3)}$$

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 A-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

$$\sigma_K^2 \cong \sum_{i=1}^{3} \left(\frac{\partial K}{\partial X_i}\right)_\mu^2 \sigma_i^2 \quad . \qquad \text{(A – 4)}$$

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

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

$$\cong \left(C_o r_o^2\right)^2 \left[2.89\left(\frac{\mu_1^{1.7}\mu_3}{\mu_2^2}\right)^2 \left(\frac{\sigma_1}{\mu_1}\right)^2 + 4\left(\frac{\mu_1^{1.7}\mu_3}{\mu_2^2}\right)^2 \left(\frac{\sigma_2}{\mu_2}\right)^2 + \left(\frac{\mu_1^{1.7}\mu_3}{\mu_2^2}\right)^2 \left(\frac{\sigma_3}{\mu_3}\right)^2\right] \qquad \text{(A - 6)}$$

$$\cong \left(C_o r_o^2 \frac{\mu_1^{1.7} \mu_3}{\mu_2^2} \right)^2 \left[2.89 \left(\frac{\sigma_1}{\mu_1} \right)^2 + 4 \left(\frac{\sigma_2}{\mu_2} \right)^2 + \left(\frac{\sigma_3}{\mu_3} \right)^2 \right] \quad . \qquad (A-7)$$

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

$$\frac{\sigma_K}{K(\mu)} \cong \left[2.89 \left(\frac{\sigma_V}{\mu_V} \right)^2 + 4 \left(\frac{\sigma_r}{\mu_r} \right)^2 + \left(\frac{\sigma_Q}{\mu_Q} \right)^2 \right]^{\frac{1}{2}} \quad . \qquad (A-8)$$

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 $c_K = \sigma_K/\mu_K$. With similar notation for the coefficients of variation for the other variables, equation A-8 can be written

$$c_K \cong \sqrt{2.89 c_V^2 + 4 c_r^2 + c_Q^2} \quad . \qquad (A-9)$$

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 3.4.1-4, can be used as estimates for the quantities needed in equation A-9. 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 A-9 gives $c_K \cong 0.17$. Thus, the estimated standard error of the PA kerma is $0.17 \times 0.044 = 0.007$ 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 three 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%.

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ATTACHMENT 3B
ORGAN DOSE EQUIVALENTS FOR LUMBAR SPINE EXAMINATIONS

Lumbar spine examinations might have occurred in the early days at PGDP, certainly before 1974, when the present X-ray technician was hired. They could have been made as a preemployment requirement, a practice in some industries at the time.

There is no specific information available for dose reconstruction other than that described in Tables 3-2 and 3-3 for the original GE machine. It is assumed that an examination consisted at most of five exposures: one anterior-posterior (AP), one lateral (LAT), two oblique, and one spot film. Operating voltage and current are assumed to be 90 kVp and 300 mA, with exposure times of 1 s for AP and 1.5 s for LAT, respectively. Under these conditions, the organ dose equivalents can be calculated for these two views by the method used in this TBD. ICRP (1982) does not include the other three. In the absence of other information, initial organ dose equivalents H_{LS} to be used for lumbar spine dose reconstruction are estimated to be those from all five views, roughly approximated as 2.5 times the sum of the AP and LAT dose equivalents. Values of H_{LS} are given in Table B-1.

The calculation proceeds as in the main document. Analogous to equation (3.3-1), one has for the lumbar spine examination

$$Q_{AP} = (300\ \text{mA})(1\ \text{s}) = 300\ \text{mAs} \quad \text{and} \quad Q_{LAT} = (300\ \text{mA})(1.5\ \text{s}) = 450\ \text{mAs}\ . \tag{B-1}$$

As before, a 5-cm thickness is allowed for the cassette. The same body thicknesses of 26 cm and 34 cm, respectively, are assumed for the AP and LAT views. The lumbar spine SID = 102 cm (ICRP 1982). Therefore, for the SSD,

$$r_{AP} = 102 - 31 = 71\ \text{cm} \quad \text{and} \quad r_{LAT} = 102 - 39 = 63\ \text{cm}\ . \tag{B-2}$$

From Table B.3 in (NCRP 1989), one finds for the kerma at the distance r_o = 60 cm,

$$K_o = \frac{1.6\ \text{cGy}}{100\ \text{mAs}} \times 1\ \text{rad cGy}^{-1} = 0.016\ \text{rad (mAs)}^{-1}\ . \tag{B-3}$$

The kerma values at skin entrance for the two views are

$$K_{AP} = \frac{0.016\ \text{rad}}{\text{mAs}} \left(\frac{60}{71}\right)^2 (300\ \text{mAs}) = 3.4\ \text{rad} \tag{B-4}$$

and

$$K_{LAT} = \frac{0.016\ \text{rad}}{\text{mAs}} \left(\frac{60}{63}\right)^2 (450\ \text{mAs}) = 6.5\ \text{rad}\ . \tag{B-5}$$

The procedures used for calculating the organ dose equivalents in Tables 3-6 and 3-7 were applied to the lumbar spine AP and LAT views for the GE machine in use from 1952 to February 1975. As in (Kathren et al. 2003), a beam quality HVL of 2.5 mm Al was assumed, and substitute projections were used for some organs to approximate the lack of good collimation. The total dose equivalents H_{LS} for

the thyroid and eye/brain were estimated to be in the same ratios to the thymus as in Table 3-8. The dose equivalents for the breast were approximated by those for the lung. The resulting estimates of the organ dose equivalents H_{AP} and H_{LAT} calculated for the two lumbar spine views are given in Table B-1. The last column gives the estimated organ dose equivalents for the total of five assumed exposures, approximated by

$$H_{LS} = 2.5(H_{AP} + H_{LAT}) \ . \qquad \text{(B-6)}$$

These values for H_{LS} can be used as rough first approximations for lumbar spine dose reconstruction in the absence of other information.

Table B-1. Organ dose equivalents for lumbar spine examinations.

Organ	Dose equivalent (mrem)		
	H_{AP}	H_{LAT}	H_{LS}
Bone marrow (active)	130.	140.	680.
Bone surface	270.	91.	900.
Breast (female)	270.	91.	900.
Colon/rectum	790.	370.	2900.
Esophagus	270.	91.	900.
Eye/brain	---	---	340.
Liver/gall bladder	270.	91.	900.
Lungs	270.	91.	900.
Ovaries	790.	370.	2900.
Remainder	270.	91.	900.
Stomach	270.	91.	900.
Testes	61.	21.	210.
Thymus	270.	91.	900.
Thyroid	---	---	450.
Urinary/bladder	790.	370.	2900.
Uterus	1000.	280.	3200.