



**ORAU TEAM
Dose Reconstruction
Project for NIOSH**

Oak Ridge Associated Universities | Dade Moeller & Associates | MJW Corporation

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ACRONYMS AND ABBREVIATIONS

| | |
|---------|----------------------------------------------------------------|
| AP | anterior-posterior (X-ray view) |
| 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 view) |
| mA | milliamperere |
| mAs | milliamperere second |
| mm | millimeter |
| mR | milliroentgen |
| mrad | millirad |
| mrem | millirem |
| NIOSH | National Institute for Occupational Safety and Health |
| PA | posterior-anterior (X-ray view) |
| 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 causation¹] guidelines established under subsection (c) ...” [42 U.S.C. § 7384n(b)]. Neither the statute nor the POC 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. 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 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.

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 A.

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. There is no evidence that PGDP ever used fluoroscopy for required chest X-ray examinations.

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. It was replaced by a Picker unit, which served from March 1975 through December 1995. The present equipment has been in operation since January 1996. Quality assurance has been verified regularly by the Food and Drug Administration and the Commonwealth of Kentucky, as well as by in-house surveys. 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. 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.

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. 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.

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). 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, 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. Rounded off, these values for the PA and LAT views, respectively, are:

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

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

| Body size (number of males, females) | View | 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:

$$K_o = \frac{0.19 \text{ cGy}}{100 \text{ mAs}} \times \frac{1 \text{ rad}}{\text{cGy}} = \frac{1.9 \times 10^{-3} \text{ rad}}{\text{mAs}} \quad (3-2)$$

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

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

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

For the PA 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:

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

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

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

and

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

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 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 3-5 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 views for all persons in this TBD, $K_{PA} = 0.044 \text{ rad}$, 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. 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 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 (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 AI for 1952 to February 1975 (ORAUT 2005) and 3.5 mm AI for March 1975 to the present, are assumed. 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:

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

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: $0.20 \times 92 = 18$ mrem (males) | LAT: $0.50 \times 37 = 19$ mrem (males) |
| $0.20 \times 86 = 17$ mrem (females) | $0.50 \times 29 = 15$ mrem (females) |

March 1975 to present:

| | |
|-------------------------------------------|-----------------------------------------|
| PA: $0.044 \times 146 = 6.4$ mrem (males) | LAT: $0.20 \times 61 = 12$ mrem (males) |
| $0.044 \times 141 = 6.2$ mrem (females) | $0.20 \times 48 = 9.6$ 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.

| Organ | Dose equivalent (rem) ^a | | | |
|----------------------|------------------------------------|----------------------------|----------------------------|----------------------------|
| | 1952–February 1975 | | March 1975–present | |
| | 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), other 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 (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

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 | 6.4E-03 | 6.9E-02 | 2.7E-03 | 3.0E-02 |
| | | Skin | 2.7E-01 | 6.8E-01 | 6.2E-02 | 2.8E-01 |

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).

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. 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 views were made, the posterior skin (Table 3-7) received a dose equivalent of 6.2×10^{-2} rem (with backscatter) from the PA view plus radiation 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 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 views 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.

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 B describes this procedure. For uncertainties of 10% in r and 5% in Q and the voltage, it is suggested that $K_{PA} = 0.044 \pm 0.015$ 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.

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_0 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 B) 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%. |

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.

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.

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 |

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:

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

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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
ORGAN DOSE EQUIVALENTS FOR LUMBAR SPINE EXAMINATIONS

Page 1 of 2

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 a preemployment requirement, a practice in some industries at the time.

There is no specific information available for dose reconstruction other than that listed 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 LAT, two oblique, and one spot film. Operating voltage and current are assumed to be 90 kVp and 300 mA, respectively, with exposure times of 1 s for AP and 1.5 s for LAT, respectively. Under these conditions, organ dose equivalents can be calculated for the two views by the method used in this TBD. ICRP (1983) 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, unless otherwise noted. Table A-1 lists values of H_{LS} .

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

| Organ | Dose equivalent (rem) | | |
|---------------------------|-----------------------|-----------|----------------------|
| | H_{AP} | H_{LAT} | H_{LS} |
| Bone marrow (active) | 1.3E-01 | 1.4E-01 | 6.8E-01 |
| Bone surface | 2.7E-01 | 9.1E-02 | 9.0E-01 |
| Breast (female) | 2.7E-01 | 9.1E-02 | 9.0E-01 |
| Colon/rectum | 7.3E-01 | 3.1E-01 | 2.6E-00 |
| Esophagus | 2.7E-01 | 9.1E-02 | 9.0E-01 |
| Eye/brain | 1.0E-03 | 6.5E-05 | 3.4E-01 ^a |
| Liver/gall bladder/spleen | 2.7E-01 | 9.1E-02 | 9.0E-01 |
| Lungs | 2.7E-01 | 9.1E-02 | 9.0E-01 |
| Ovaries | 7.3E-01 | 3.1E-01 | 2.6E-00 |
| Remainder | 2.7E-01 | 9.1E-02 | 9.0E-01 |
| Stomach | 2.7E-01 | 9.1E-02 | 9.0E-01 |
| Testes ^b | 6.1E-02 | 2.1E-02 | 2.1E-01 |
| Thymus | 2.7E-01 | 9.1E-02 | 9.0E-01 |
| Thyroid | 1.0E-03 | 6.5E-05 | 4.5E-01 ^a |
| Urinary/bladder | 7.3E-01 | 3.1E-01 | 2.6E-00 |
| Uterus | 9.8E-01 | 2.0E-01 | 3.0E-00 |

^a. Based on thymus dose equivalent.

^b. Used DCF for the abdomen.

The calculation proceeds as in the main document. Analogous to equation 3-1, one has for the lumbar spine examination

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

ATTACHMENT A
ORGAN DOSE EQUIVALENTS FOR LUMBAR SPINE EXAMINATIONS

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As before, a 5-cm thickness is allowed for the cassette. Body thicknesses of 26 and 34 cm are assumed for the AP and LAT views, respectively. The lumbar spine SID = 102 cm (ICRP 1983). Therefore, for the SSD:

$$r_{AP} = 102 - 31 = 71 \text{ cm} \quad \text{and} \quad r_{LAT} = 102 - 39 = 63 \text{ cm} \quad (\text{A-2})$$

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

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

The kerma values at skin entrance for the two views are:

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

and

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

The procedures used for calculating 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 ORAUT (2005), 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 estimated total dose equivalents H_{LS} for the thyroid and eye/brain were assumed 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. Table A-1 lists the resulting estimates of organ dose equivalents H_{AP} and H_{LAT} calculated for the two lumbar spine views. The last column lists estimated organ dose equivalents for the five assumed exposures, approximated by:

$$H_{LS} = 2.5(H_{AP} + H_{LAT}) \quad (\text{A-6})$$

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

ATTACHMENT B 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; Tsoufanidis 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:

$$K_o = C_o V^{1.7} \quad (\text{B-1})$$

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:

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

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

$$\begin{array}{llll} V = X_1 & \text{with mean } \mu_1 = \mu_V & \text{and} & \text{standard deviation } \sigma_1 = \sigma_V \\ r = X_2 & \text{with mean } \mu_2 = \mu_r & \text{and} & \text{standard deviation } \sigma_2 = \sigma_r \\ Q = X_3 & \text{with mean } \mu_3 = \mu_Q & \text{and} & \text{standard deviation } \sigma_3 = \sigma_Q \end{array}$$

The kerma can be written:

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

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:

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

ATTACHMENT B
ERROR PROPAGATION FOR KERMA

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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:

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

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

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:

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

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:

$$c_K \cong \sqrt{2.89 c_V^2 + 4 c_r^2 + c_Q^2} \quad (\text{B-7})$$

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 $\sigma_i \ll \mu_i$.

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 $\pm 5\%$. An uncertainty in the SSD r of 10 cm, or $\pm 7\%$ 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 $0.17 \times 0.044 = 0.007$ rad. With assumed normal statistics, $K_{PA} = 0.044 \pm 0.015$ 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 $\pm 34\%$. 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%.