Document Title:	Document Number: ORAUT-TKBS-0036-3
Argonne National Laboratories - East - Occupational Medical Dose	Revision: 01 PC-1
	Effective Date: 03/27/2006
	Type of Document: TBD
	Supersedes: Revision 00

Subject Expert: Theresa Lopez

Document Owner

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Approval:	Signature on File Stuart L. Hinnefeld, Health Science Administrator	Approval Date:	01/09/2006

☐ New ☐ Total Rewrite ☐ Revision ☒ Page Change

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PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
11/18/2005	00	New technical basis document for Argonne National Laboratories-East - Occupational Medical Dose. First approved issue. Initiated by Norman D. Rohrig.
01/09/2006	01	Approved revision initially converted from a page change to a revision. Incorporates additional information based on informal discussions with NIOSH. Incorporates information from review of claimant files. Clarifies that coverage begins July 1946. Moves tables closer to references in the text. Text was added and/or modified in Sections 3.1, 3.3, 3.5.2, and 3.6 (pages 5, 7, 9, 10, 11, and 13). Initiated by Norman D. Rohrig.
03/27/2006	01 PC-1	Approved page change revision. Page change initiated to revise analog/surrogate Table 3-4 on page 9 in Section 3.5.1 to remove uterus as a surrogate organ for ovaries. No sections were deleted. Training required: As determined by the Task Manager. Initiated by Norman D. Rohrig. Approval: Document Owner: Signature on File 03/20/2006 Norman D. Rohrig, TBD Team Leader Signature on File 03/17/2006 Judson L. Kenoyer, Task 3 Manager Signature on File 03/17/2006 Edward F. Maher, Task 5 Manager Signature on File 03/22/2006 Kate Kimpan, Projector Director Signature on File 03/27/2006 Stuart L. Hinnefeld, Health Science Administrator

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ACRONYMS AND ABBREVIATIONS

ANL E	Argonne National Laboratories East
AP	anterior-posterior
C.F.R.	Code of Federal Regulations
cm	centimeter
DOE	U.S. Department of Energy
EEOICPA	Energy Employees Occupational Illness Compensation Program Act of 2000
ESE	entrance skin exposure
Gy	gray
HVL	half-value layer
ICRP	International Commission on Radiological Protection
IREP	Interactive RadioEpidemiological Program
kerma	initial kinetic energy of charged particles liberated by indirectly ionizing radiation per unit mass
keV	kilo-electron volt
kVp	kilovolt peak
LAT	lateral
LS	lumbar spine
mm	millimeter
NCRP	National Council on Radiation Protection and Measurements
NIOSH	National Institute for Occupational Safety and Health
PA	posterior-anterior
PFG	photofluorography/photofluorographic
SID	source-to-image distance
SSD	source-to-skin distance
TBD	technical basis document
U.S.C.	United States Code
yr	year

3.1 INTRODUCTION

Technical basis documents (TBDs) and Site Profile documents are general working documents that provide guidance concerning the preparation of dose reconstructions at particular sites or categories of sites. They will be revised in the event additional relevant information is obtained about the affected site(s). These documents may be used to assist NIOSH in the completion of the individual work required for each dose reconstruction.

In this document the word "facility" is used as a general term for an area, building, or group of buildings that served a specific purpose at a site. It does not necessarily connote an "atomic weapons employer facility" or a "Department of Energy [DOE] facility" as defined in 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 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 [probability of causation] 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 radiation exposures 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 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.

Argonne National Laboratory was established on July 1, 1946 and this TBD is intended to cover since that date. The work was a continuation of that done by the Metallurgical Laboratory of the University of Chicago beginning in 1941 which is an Atomic Weapons Employer under EEOICPA. The job locations did not change until land and buildings were acquired for the laboratory.

As part of the requirements for employment at Argonne National Laboratories-East (ANL-E) from the 1940s to the present, all employees might have received X-rays as part of periodic physical examinations in addition to preemployment and termination X-rays. These could include annual radiographic examinations of the chest, photofluorographic (PFG) chest examinations or, after 1980,

periodic chest X-ray examinations for workers who used respirators or smoked (Stalker 2005; Lopez 2005a). Before 1960, lumbar spine (LS) X-ray examinations were routinely performed (Stalker 2005). NIOSH, in its role to reconstruct occupational dose under EEOICPA, has classified diagnostic medical x-rays administered in conjunction with routine or special physical examinations required for employment as occupational exposures (NIOSH 2002). This TBD discusses medical exposures required as a condition of employment; it does not include diagnostic and therapeutic procedures not required for employment.

The following sections describe the methodology used to estimate absorbed dose from X-ray exposure for ANL-E workers. In the absence of available data, assumptions are claimant-favorable. This section provides introductory text. Section 3.2 provides background information for this TBD analysis. Section 3.3 describes X-ray examination frequency at ANL-E. Section 3.4 provides information on equipment and techniques used at ANL-E, including assumptions necessitated by lack of protocol, measurement, or records data. Section 3.5 provides organ dose estimates by calendar year and type of X-ray. Section 3.6 documents uncertainties.

3.2 BACKGROUND

As described in *Protection of the Patient in Diagnostic Radiology* (ICRP 1982), the amount of energy absorbed in the body and its distribution in specific organs can be determined by measurement or calculation. Absorbed dose in tissue, measured in units of gray (Gy), is equal to the energy absorbed per unit mass at a point in the human body.

The radiation dose received in a given examination varies widely throughout the body. Doses are highly dependent on the technical factors employed, characteristics of the equipment, collimation of the beam, and number of films taken. The general equation for total annual occupational medical dose provided by NIOSH (2002) guidelines is:

$$D_{om} = \Sigma n D_i \qquad (3\text{–}1)$$

where

D_{om} = occupational medical dose
n = Number of examinations in a calendar year
D_i = dose from the X-ray procedure

The NIOSH guidelines state that medical records should contain the dates, types, and number of X-ray examinations, and that if there is no known information about the energy spectra, values should be assumed conservatively to be in the 30- to 250-kV photon range (a claimant-favorable assumption) (NIOSH 2002). The guidance states the assumption that the uncertainty distribution about each X-ray procedure follows a normal distribution, with D_{om} being the mean dose.

X-ray inspection data are available from 1988 to the present. For those years, measured entrance skin exposure (ESE) was used to estimate organ doses. For years prior to 1988, default estimates have been used until site-specific data can be identified.

3.3 EXAMINATION FREQUENCY

The frequency and type of X-ray examinations for ANL-E workers from 1940 to the present have been determined through interviews with ANL-E medical personnel (Stalker 2005; Lopez 2005a; Lopez 2005b). Written or historical protocol noting the frequency of chest X-ray examinations as a function

of job category has not been located. However, it is believed that chest X-ray examinations were performed at hire, annually, and at termination from the 1940s through 1980, and that both posterior-anterior (PA) and lateral (LAT) views were taken. Through 1958, stereo PA views were taken. It is possible that chest PFG was performed until 1956; it is known to have been performed in the 1940s and would likely have ended in 1949 when the medical department moved from the University of Chicago. However, persons receiving their annual x-ray examination at the University of Chicago may have received PFG examinations until 1956 as evidenced in a review of claimant files. In addition, anterior-posterior (AP) and LAT LS X-rays were performed at the time of hire from 1946 through 1960 (Stalker 2005; Lopez 2005a; Lopez 2005b; four views assumed). From 1980 to the present, PA chest X-rays have been taken at hire, every 4 yr while employed if the worker wore a respirator or smoked, and at termination. Table 3-1 summarizes examination frequency and all known machine types for ANL-E. Only one exception to the frequency denoted below was found in a review of claimant files: one worker received chest x-rays approximately every 3 months for 1 year due to working with tuberculosis infected monkeys. The reason for the x-rays was noted in the claimant's medical files; it did not appear in the claimant's description of work. More frequent chest x-rays were also noted in worker files for pneumonia and neoplasm diagnosis, but these are outside the scope of the TBD.

Table 3-1. X-ray equipment and examination frequency at ANL-E by year.[a]

Date	Procedure	Frequency	Machine type	Source of dose estimate
1946-1956	PFG Chest X-ray: Chest stereo PA and single LAT LS AP and LAT (4 views)	Chest: Hire, annual, and termination LS: Hire only	Unknown; performed at University of Chicago	Default values from ORAU (2005)
1957-1959	X-ray: Chest stereo PA and single LAT LS AP and LAT (4 views)	Chest: Hire, annual, and termination LS: Hire only	GE (unknown model)	Default values from ORAU (2005)
1960-1969	X-ray Chest PA and LAT	Hire, annual, and termination	GE (unknown model)	Default values from ORAU (2005)
1970-1980	X-ray Chest PA and LAT	Hire, annual, and termination	GE DXD-350 Single-phase	Default values from ORAU (2005)
1981-1987	X-ray Chest PA	Hire, every 4 yr for some workers	GE DXD-350 Single-phase	Default values from ORAU (2005)
1988-present	X-ray Chest PA	Hire, every 4 yr for some workers	GE Advantix Three-phase	Measured ESE (Stalker 2005; X-ray Survey 2005)

a. Stalker (2005).

3.4 EQUIPMENT AND TECHNIQUES

The analysis assumed that ANL-E radiological practices followed standards of medical practice to minimize dose to the patient; however, the type of equipment, technique factors, and machine calibrations used before 1988 are not known.

This TBD uses default dose estimates from *Technical Information Bulletin: Dose Reconstruction from Occupationally Related Diagnostic X-ray Procedures* (ORAU 2005) to provide organ dose estimates from occupational X-ray examinations administered at ANL-E from 1946 through 1969 (pre-1970), 1970 to 1985, and 1986 to 1987. For the years before 1970, the default values assume minimal beam collimation and a half-value layer (HVL) of 2.5 mm Al. For 1970 to 1985, the default values assume beam collimation and an HVL of 2.5 mm Al. For years after 1985 through 1987, the default values assume collimation and an HVL of 4.0 mm Al. For 1988 and later, doses have been calculated from measured ESE for PA chest X-rays (Stalker 2005; X-ray Survey 2005).

Table 3-1 lists the assumed type and frequency of exposure by period. Records of machine settings prior to 1988 are not available, so this TBD uses default estimates for LAT and PA chest X-rays and LS X-rays from ORAU (2005).

Efforts will continue to locate related additional site-specific information. Until the location of more accurate records, these assumptions provide the only available estimates.

3.5 ORGAN DOSE ESTIMATES

This section discusses organ dose estimates. Section 3.5.1 describes the methodology used to estimate these doses, and Section 3.5.2 discusses results.

3.5.1 Parameters and Estimation Method

This analysis used measured ESE data for 1988 and later. It used ESE data for PA chest X-ray (and for one period, LAT chest X-ray); when necessary, the estimated LAT chest X-ray ESE was 2.5 times the PA chest ESE (ORAU 2005). Table 3-2 lists measured and estimated ESE. ESE (units of gray) was multiplied by the appropriate dose conversion factor to estimate organ doses.

Table 3-2. Entrance kerma by procedure and period.

Period	Entrance kerma, cGy, PA chest	Entrance kerma, cGy, LAT chest	ESE, rem, AP lumbar spine	ESE, rem, LAT lumbar spine	ESE, chest PFG, cGy
1946-1948	N/A[a]	N/A	4	10	3.0
Pre-1970[b]	0.2	0.5	4	10	N/A
1970-1985[b]	0.1	0.25	N/A	N/A	N/A
1985-1987[b]	0.05	0.13	N/A	N/A	N/A
1988-1989[c]	0.0105	0.026	N/A	N/A	N/A
1990-1991[c]	0.009	0.0225	N/A	N/A	N/A
1992-1993[c]	0.006	0.015	N/A	N/A	N/A
1994-1995[c]	0.0135	0.0338	N/A	N/A	N/A
1996-1997[c]	0.0133	0.0333	N/A	N/A	N/A
1998-1999[c]	0.0068	0.017	N/A	N/A	N/A
2000-2001[c]	0.0069	0.0173	N/A	N/A	N/A
2002-2004[c]	0.0069	0.0173	N/A	N/A	N/A
2005[d]	0.0078	0.0138	N/A	N/A	N/A

a. N/A – Not Applicable
b. ORAU (2005).
c. Measured ESE for PA Chest. LAT entrance kerma is 2.5 × PA Chest ESE.
d. Measured LAT ESE available for this year only (X-ray Survey 2005).

For the years before 1988, organ dose estimates are based on the values in ORAU (2005). Table 3-2 lists default entrance kerma for PA and LAT chest X-rays from ORAU (2005). Table 3-3 lists dose conversion factors (DCFs).

The International Commission on Radiological Protection (ICRP) tables used to estimate absorbed dose (ICRP 1982) do not include all the organs in the Interactive RadioEpidemiological Program (IREP). For organs in IREP that are not identified in the ICRP tables, use the dose conversion coefficient that is anatomically closest to the IREP-specified organs to estimate dose. For example, the factor for lung can be applied to all other organs in the thoracic cavity, such as the esophagus and bone surface. For abdominal organs (bladder, colon), use the dose coefficient for ovaries. This approach should be either claimant-favorable or neutral. Table 3-4 lists analogs for IREP organs, as originally presented in ORAU (2005).

Table 3-3. Modified ICRP DCFs (mGy per Gy air kerma); absorbed dose (1 mGy) for organs at various Al HVL for PFG and radiography (ORAU 2005; ICRP 1982).[a]

	Dose conversion factors–LS		Dose conversion factors PFG chest PA	Dose conversion factors–chest					
	Pre-1970 (2.0-mmAl HVL)	Pre-1970 (2.0-mmAl HVL)		Pre-1970 (2.5-mm Al HVL)		1970-1985 (2.5-mm Al HVL)		Post-1985 (4.0-mm Al HVL)	
Organ	LAT	AP	(Pre-1970)	LAT	PA	LAT	PA	LAT	PA
Thyroid	0.1	0.2	174[b]	137	174[b]	115	32	164	78
Eye/brain	0.1	0.2	32	137	32	115	32	164	78
Ovaries	N/A[c]	N/A[c]	N/A	N/A	N/A	0.6	1	2.5	5.2
Liver/gall bladder/spleen	10[d]	62[d]	451	220	451	220	451	351	674
Urinary bladder	N/A[d]	N/A[d]	N/A	N/A	N/A	0.6	1	2.5	5.2
Colon/rectum	N/A[d]	N/A[d]	N/A	N/A	N/A	0.6	1	2.5	5.2
Testes	N/A[c]	N/A[c]	N/A	N/A	N/A	0.1	0.01	0.1	0.01
Lungs (male)	10	62	419	193	419	193	419	313	628
Lungs (female)	10	62	451	220	451	220	451	351	674
Thymus[d]	10	62	451	220	451	220	451	351	674
Esophagus[d]	10	62	451	220	451	220	451	351	674
Stomach[d]	10	62	451	220	451	220	451	351	674
Bone surfaces[d]	10	62	451	220	451	220	451	351	674
Remainder[d]	10	62	451	220	451	220	451	351	674
Female breast	9.5[e]	18[e]	49	255	49	255	49	343	116
Uterus	20	217	N/A	N/A	N/A	0.6	1.3	2.1	5.2
Bone marrow (male)	15	24	92	37	92	37	92	76	178
Bone marrow (female)	15	24	86	29	86	29	86	59	172
Skin[c]	1.32[f]	1.32[f]	1.35[f]	1.35[f]	1.35[f]	1.35[f]	1.35[f]	1.40[f]	1.40[f]

a. Table 3-4 lists organ doses for all organs.
b. Per ORAU (2005), DCF for AP c-spine corrected for depth by 0.2
c. Organ dose values for the testes and ovaries for lumbar spine reflect actual measurements reported in Lincoln and Gupton (1958).
d. Using analogs listed in Table 3-4.
e. DCFs for lumbar spine examination not given in ICRP (1982). Values for the respective upper gastrointestinal examinations were used instead.
f. Calculated using backscatter factor from NCRP 102 (1989, Table B-3) (ORAU 2005); see Table 3-5.

Table 3-4. Analogs for IREP organs not specified in ICRP (1982).

Anatomical location	ICRP 34 reference organ	IREP organ analogs[a]
Thoracic cavity	Lung	Thymus, esophagus, stomach, bone surface, liver/gall bladder, remainder organs
Abdominal cavity	Ovaries	Urinary bladder, colon/rectum
Head and neck	Thyroid	Eye/brain

a. ORAU (2005).

3.5.2 Organ Dose Estimates for ANL-E Workers

Table 3-5 lists default organ doses from PA PFG examinations (ORAU 2005) for 1941 through 1956 and Table 3-6 lists default organ doses (assumes 4 views) from LAT and AP lumbar spine X-rays that dose reconstructors should use for 1946 through 1959. If medical records show only 2 views, the dose reconstructor should divide the values by 2 (Lopez 2005b). Additionally, if it is known that medical x-ray examinations were conducted at ANL-E facilities rather than at the University of Chicago, then it is unlikely that PFG was performed after 1949. However, a review of claimant files showed that PFG was possible up through 1956 if the claimant received annual physical examinations at the University of Chicago.

Table 3-7 lists default and calculated organ dose estimates from LAT and PA chest X-ray examinations for each period (before 1970, 1970 to 1985, and 1986-1987, and two year periods from 1988 through 2005). The estimates for exposure from chest X-rays for the pre-1988 periods are from default values in Table 5 of ORAU (2005) while site-specific information is being obtained. Note that stereo PA examinations were routinely performed through 1958.

Table 3-5. Organ dose estimates for chest PFG (rem), 1946 - 1956, as presented in ORAU (2005).

Organ	PA (rem)
Thyroid	5.22E-01
Eye/brain	9.60E-02
Ovaries	2.5E-02[a]
Liver/gall bladder/spleen	1.35E+00
Urinary bladder	2.5E-02[a]
Colon/rectum	2.5E-02[a]
Testes	5.0E-03[a]
Lungs (male)	1.26E+00
Lungs (female)	1.35E+00
Thymus	1.35E+00
Esophagus	1.35E+00
Stomach	1.35E+00
Bone surfaces	1.35E+00
Remainder	1.35E+00
Female breast	1.47E-01
Uterus	2.5E-02[a]
Bone marrow (male)	2.76E-01
Bone marrow (female)	2.58E-01
Skin[b]	4.05E+00

a. Modified from Webster and Merrill (1957), as presented in ORAU (2005).
b. Calculated in ORAU (2005) using backscatter factor of 1.35 from NCRP 102 (1989, Table B-3).

3.6 UNCERTAINTIES

As defined in ORAU (2003, 2005), *error* is deviation from the correct, true, or conventionally accepted value of a quantity, and *uncertainty* is in terms of the potential range of a stated, measured, or assumed or otherwise determined value of a quantity. Error and uncertainty provide an indication of confidence in the dose estimates. Uncertainty, expressed in terms of a confidence level, is a more appropriate term than error, which implies that the actual value is known. Uncertainty, stated as a probability of falling within a stated range, includes precision and reproducibility of the measurement as well as accuracy (that is, how close the estimate comes to the actual value).

Although many factors can introduce uncertainty and error into X-ray exposures, five factors contribute the most uncertainty to the dose estimate: measurement error, variation in applied kilovoltage, variation in beam current, variation in exposure time, and source-to-skin distance (SSD). Film speed, the use of screens, or the use of grids would not affect the beam output intensity. The lack of historical records for these measurements for most years at ANL-E introduces a large uncertainty into the dose estimates that cannot be readily quantified, although there is no apparent reason to believe that practices at ANL-E or its medical subcontractors were different from those at other facilities or from recommended standards of the medical community at the time. Therefore, the use of default estimates and reliance on information from other DOE sites when site-specific information was unavailable is likely to approximate X-ray performance at ANL-E closely. The following estimates of uncertainty associated with X-ray exposure are from ORAU (2005), on which this TBD analysis relied for default information in the absence of site-specific records. The analysis also used X-ray inspection records for 1988 and later; such records indicate that X-ray equipment at ANL-E was performing within an acceptable range and without any problems. The uncertainty estimates below will probably overestimate uncertainty for those years.

Table 3-6. Organ doses from lumbar spine X-ray, 1946-1959 (ORAU 2005).

Organ	Estimated dose[a,b,c] HVL = 2.0 mm Al (collimated); Entrance kerma = 0.20 cGy	
	LAT (rem)	AP (rem)
Thyroid	1.00E-04	8.00E-04
Eye/brain	1.00E-04	8.00E-04
Ovaries	1.52E+00[d]	1.12E+00[d]
Liver/gall bladder/spleen	1.00E-01	2.48E-01
Urinary bladder	1.52E+00[d]	1.12E+00[d]
Colon/rectum	1.52E+00[d]	1.12E+00[d]
Testes	1.12E+01[d]	5.40E-02[d]
Lungs	1.00E-01	2.48E-01
Thymus	1.00E-01	2.48E-01
Esophagus	1.00E-01	2.48E-01
Stomach	1.00E-01	2.48E-01
Bone surfaces	1.00E-01	2.48E-01
Remainder	1.00E-01	2.48E-01
Female breast	9.50E-02	7.20E-02
Uterus	2.00E-01	8.68E+00
Bone marrow	1.50E-01	9.60E-02
Skin[e]	1.32E+01	5.28E+00

a. Source-to-image distance (SID) = 99 cm.
b. Image receptor size 35.6 cm by 43.2 cm.
c. Value is doubled to account for two exposures.
d. Organ dose values the testes and ovaries (and analogs) for lumbar spine reflect actual measurements reported in Lincoln and Gupton (1958).
e. Skin dose values include backscatter factors of 1.32 from Table B.8 of NCRP 102 (1989).

Table 3-7. Organ dose estimates for chest X-rays (rem).

Organ	Pre-1970 Estimated dose[a,b,c] HVL = 2.5 mm Al (uncollimated)		1970-1985 Estimated dose[a,b,c] HVL = 2.5 mm Al (collimated)		1986-1987 Estimated dose[a,b] HVL = 4.0 mm Al (collimated)		1988-1989 Estimated dose[a,b] HVL = 4.0 mm Al (collimated)		1990-1991 Estimated dose[a,b] HVL = 4.0 mm Al (collimated)	
	LAT	PA	LAT	PA	LAT	PA	LAT	PA	LAT	PA
Thyroid	6.85E-02	3.48E-02	2.88E-02	3.20E-03	2.13E-02	3.90E-03	4.31E-03	8.19E-04	3.69E-03	7.02E-04
Eye/brain	6.85E-02	6.4E-03	2.88E-02	3.20E-03	2.13E-02	3.90E-03	4.31E-03	8.19E-04	3.69E-03	7.02E-04
Ovaries	1.3E-02[c]	2.5E-02[c]	1.50E-04	1.00E-04	3.25E-04	2.60E-04	6.56E-05	5.46E-05	5.63E-05	4.68E-05
Liver/gall bladder/ spleen	1.10E-01	9.02E-02	5.5E-02	4.5E-02	4.56E-02	3.37E-02	9.21E-03	7.08E-03	7.90E-03	6.07E-03
Urinary bladder	1.3E-02[c]	2.5E-02[c]	1.50E-04	1.00E-04	3.25E-04	2.60E-04	6.56E-05	5.46E-05	5.63E-05	4.68E-05
Colon/rectum	1.3E-02[c]	2.5E-02[c]	1.50E-04	1.00E-04	3.25E-04	2.60E-04	6.56E-05	5.46E-05	5.63E-05	4.68E-05
Testes	2.5E-03[c]	5.00E-03[c]	2.5E-05	1.00E-06	1.30E-05	5.00E-07	2.63E-06	1.05E-07	2.25E-06	9.00E-08
Lungs	1.1E-01	9.02E-02	5.50E-02	4.51E-02	4.56E-02	3.37E-02	9.21E-03	7.08E-03	7.90E-03	6.07E-03
Thymus	1.1E-01	9.02E-02	5.50E-02	4.51E-02	4.56E-02	3.37E-02	9.21E-03	7.08E-03	7.90E-03	6.07E-03
Esophagus	1.1E-01	9.02E-02	5.50E-02	4.51E-02	4.56E-02	3.37E-02	9.21E-03	7.08E-03	7.90E-03	6.07E-03
Stomach	1.1E-01	9.02E-02	5.50E-02	4.51E-02	4.56E-02	3.37E-02	9.21E-03	7.08E-03	7.90E-03	6.07E-03
Bone surfaces	1.1E-01	9.02E-02	5.50E-02	4.51E-02	4.56E-02	3.37E-02	9.21E-03	7.08E-03	7.90E-03	6.07E-03
Remainder	1.1E-01	9.02E-02	5.50E-02	4.51E-02	4.56E-02	3.37E-02	9.21E-03	7.08E-03	7.90E-03	6.07E-03
Female breast	1.28E-01	9.8E-03	6.38E-02	4.90E-03	4.46E-02	5.80E-03	9.00E-03	1.22E-03	7.72E-03	1.04E-03
Uterus	1.3E-02[c]	2.5E-02[c]	1.50E-04[c]	1.30E-04[c]	2.73E-04	2.60E-04	5.51E-05	5.46E-05	4.73E-05	4.68E-05
Bone marrow	1.85E-02	1.84E-02	9.25E-03	9.20E-03	9.88E-03	8.90E-03	2.00E-03	1.87E-03	1.71E-03	1.60E-03
Skin[d,e]	6.75E-01	2.7E-01	3.38E-01	1.35E-01	1.82E-01	7.00E-02	3.73E-02	1.49E-02	3.20E-02	1.28E-02

Table 3-7 (continued). Organ dose estimates for chest X-rays (rem).

Organ	1992-1993 Estimated dose[a,b] HVL = 4.0 mm Al (collimated)		1994-1995 Estimated dose[a,b] HVL = 4.0 mm Al (collimated)		1996-1997 Estimated dose[a,b] HVL = 4.0 mm Al (collimated)		1998-1999 Estimated dose[a,b] HVL = 4.0 mm Al (collimated)		2000-2004 Estimated dose[a,b] HVL = 4.0 mm Al (collimated)	
	LAT	PA	LAT	PA	LAT	PA	LAT	PA	LAT	PA
Thyroid	2.46E-03	4.68E-04	5.54E-03	1.05E-03	5.45E-03	1.04E-03	2.79E-03	5.30E-04	2.83E-03	5.38E-04
Eye/brain	2.46E-03	4.68E-04	5.54E-03	1.05E-03	5.45E-03	1.04E-03	2.79E-03	5.30E-04	2.83E-03	5.38E-04
Ovaries	3.75E-05	3.12E-05	8.44E-05	7.02E-05	8.31E-05	6.92E-05	4.25E-05	3.54E-05	4.31E-05	3.59E-05
Liver/gall bladder/ spleen	5.27E-03	4.04E-03	1.18E-02	9.10E-03	1.17E-02	8.96E-03	5.97E-03	4.58E-03	6.05E-03	4.65E-03
Urinary bladder	3.75E-05	3.12E-05	8.44E-05	7.02E-05	8.31E-05	6.92E-05	4.25E-05	3.54E-05	4.31E-05	3.59E-05
Colon/rectum	3.75E-05	3.12E-05	8.44E-05	7.02E-05	8.31E-05	6.92E-05	4.25E-05	3.54E-05	4.31E-05	3.59E-05
Testes	1.50E-06	6.00E-08	3.38E-06	1.35E-07	3.33E-06	1.33E-07	1.70E-06	6.80E-08	1.73E-06	6.90E-08
Lungs	5.27E-03	4.04E-03	1.18E-02	9.10E-03	1.17E-02	8.96E-03	5.97E-03	4.58E-03	6.05E-03	4.65E-03
Thymus	5.27E-03	4.04E-03	1.18E-02	9.10E-03	1.17E-02	8.96E-03	5.97E-03	4.58E-03	6.05E-03	4.65E-03
Esophagus	5.27E-03	4.04E-03	1.18E-02	9.10E-03	1.17E-02	8.96E-03	5.97E-03	4.58E-03	6.05E-03	4.65E-03
Stomach	5.27E-03	4.04E-03	1.18E-02	9.10E-03	1.17E-02	8.96E-03	5.97E-03	4.58E-03	6.05E-03	4.65E-03
Bone surfaces	5.27E-03	4.04E-03	1.18E-02	9.10E-03	1.17E-02	8.96E-03	5.97E-03	4.58E-03	6.05E-03	4.65E-03
Remainder	5.27E-03	4.04E-03	1.18E-02	9.10E-03	1.17E-02	8.96E-03	5.97E-03	4.58E-03	6.05E-03	4.65E-03
Female breast	5.15E-03	6.96E-04	1.16E-02	1.57E-03	1.14E-02	1.54E-03	5.83E-03	7.89E-04	5.92E-03	8.00E-04
Uterus	3.15E-05	3.12E-05	7.09E-05	7.02E-05	6.98E-05	6.92E-05	3.57E-05	3.54E-05	3.62E-05	3.59E-05
Bone marrow	1.14E-03	1.07E-03	2.57E-03	2.40E-03	2.53E-03	2.37E-03	1.29E-03	1.21E-03	1.31E-03	1.23E-03
Skin[e]	2.13E-02	8.52E-03	4.79E-02	1.92E-02	4.72E-02	1.89E-02	2.41E-02	9.66E-03	2.45E-02	9.80E-03

Organ	2005 Estimated dose[a,b] HVL = 4.0 mm Al (collimated)	
	LAT	PA
Thyroid	2.23E-03	6.08E-04
Eye/brain	2.23E-03	6.08E-04
Ovaries	3.40E-05	4.06E-05
Liver/gall bladder/spleen	4.77E-03	5.26E-03
Urinary bladder	3.40E-05	4.06E-05
Colon/rectum	3.40E-05	4.06E-05
Testes	1.36E-06	7.80E-08
Lungs	4.77E-03	5.26E-03
Thymus	4.77E-03	5.26E-03
Esophagus	4.77E-03	5.26E-03
Stomach	4.77E-03	5.26E-03
Bone surfaces	4.77E-03	5.26E-03
Remainder	4.77E-03	5.26E-03
Female breast	4.66E-03	9.05E-04
Uterus	2.86E-05	4.06E-05
Bone marrow	1.03E-03	1.39E-03
Skin[e]	1.44E-03	1.11E-02

a. SID = 183 cm.
b. Image receptor size 35.6 cm by 43.2 cm.
c. Modified from Webster and Merrill (1957) as presented in ORAU (2005).
d. Calculated in ORAU (2005) using backscatter factor of 1.35 from NCRP 102 (1989, Table B-3) for skin dose estimates through 1985.
e. Calculated in ORAU (2005) using backscatter factor of 1.40 from NCRP 102 (1989, Table B-3) for skin dose estimates after 1985.

ORAU (2005) reports that X-ray doses are derived largely from actual measurements of X-ray machine output with R-meters or similar ionization chamber devices. These typically had an uncertainty of ±2% for photon energies below 400 keV, if properly calibrated and used. Although more current machinery could have a smaller uncertainty, +2% is assumed to be conservative.

Variation in applied voltage generally falls within ±5% of the machine setting. Beam intensity is approximately proportional to the 1.7 power of the kilovoltage, resulting in an uncertainty of approximately +9% in relation to beam intensity for voltages in the 110- to 120-kVp range. Variations in tube current are normal and generally small. As the tube current drops, beam intensity falls in

direct proportion. Large decreases in beam output would be readily detectable and would indicate the need for machine maintenance or, as a temporary measure, an increase in the current or voltage to provide the necessary intensity for proper radiography. ORAU (2005) estimates the variation in tube current to be approximately ±5% for this parameter.

Exposure time can significantly affect the dose received from radiography (exposure times are a fraction of second). Even a small variation in exposure time due to timer error can significantly change beam output. Because early X-ray machine timers are known to have been inaccurate, ORAU (2003, 2005) assume uncertainty in beam output due to timers to be ±25%.

SSD can contribute to variability because the ESE is determined by this distance. Variations result from accuracy of positioning as well as patient size (thickness). As expressed in ORAU (2003, 2005), this is generally thought to vary by no more than a few centimeters, with an upper limit of 7.5 cm (±10%).

A potentially large source of uncertainty for ANL-E is the number and type of X-rays taken. As noted above, interviews of current medical personnel indicated that the current protocol is one PA chest X-ray at hire, then as needed, but not more frequently than every 4 years. Prior to 1980, different protocols were in effect. No official historical protocol has been found, but it is reported that PFG was used prior to the medical department opening at its current location and that lumber spine X-rays were taken in years prior to at least 1960. This analysis assumed that the protocol for chest X-rays would have been consistent with those at other sites, and a review of claimant files showed that annual x-rays were most common prior to 1980. Therefore, at this time, dose reconstructors should assume an annual chest X-ray for all workers in all years prior to 1980 (stereo PA through 1958), lumbar spine X-rays at hire for all workers prior to 1960, and performance of PFG up through 1956, which is the latest reference found. The analysis assumed four views in the dose estimates presented here (AP, AP-spot, LAT, and LAT-spot), consistent with default dose estimates from ORAU (2005) until the location of more specific information.

Consistent with ORAU (2003, 2005), the TBD analysis calculated the statistical root mean square to estimate total uncertainty. The root mean square is the square root of the sum of the squares of the individual uncertainty values, and equals 28.9%. An estimate of 30% uncertainty at one sigma for a normal distribution should be entered into IREP.

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