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PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
08/24/2004	00	New technical basis document for the Pantex Plant – Occupational Medical Dose. First approved issue. Initiated by Jerome B. Martin.
12/23/2005	01	Approved issue of Revision 01. Training required: As determined by the Task Manager. Initiated by Dillard B. Shipler.
02/01/2007	02	Approved Revision 02 for organ dose assignment based on site-specific information. Added Section 3-5, Skin Dose Method Description and Section 3-8, Attributions and Annotations. Incorporates internal formal and NIOSH formal review comments. Constitutes a total rewrite of document. This revision results in an increase in assigned dose and a PER is required. Initiated by Robert C. Winslow.

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ACRONYMS AND ABBREVIATIONS

AP	anterior-posterior
cGy	centigray
CHP	Certified Health Physicist
cm	centimeter
DCF	dose conversion factor
DOE	U.S. Department of Energy
EEOICPA	Energy Employees Occupational Illness Compensation Program Act of 2000
ESE	entrance skin exposure
GE	General Electric Company
Gy	gray
HVL	half-value layer
ICRP	International Commission on Radiological Protection
in.	inch
IREP	Interactive RadioEpidemiological Program
kVp	kilovolts-peak, applied kilovoltage
LAT	lateral
m	meter
mA	milliampere
mAs	milliampere-second
mGy	milligray
mm	millimeter
mR	milliroentgen
NCRP	National Council on Radiation Protection and Measurements
NIOSH	National Institute for Occupational Safety and Health
ORAU	Oak Ridge Associated Universities
PA	posterior-anterior
POC	probability of causation
R	roentgen
s	second
TBD	technical basis document
U.S.C.	United States Code
yr	year
§	section or sections

3.1 INTRODUCTION

Technical basis documents and site profile documents are not official determinations made by the National Institute for Occupational Safety and Health (NIOSH) but are rather general working documents that provide historic background information and guidance to assist in the preparation of dose reconstructions at particular sites or categories of sites. They will be revised in the event additional relevant information is obtained about the affected site(s). These documents may be used to assist NIOSH staff in the completion of the individual work required for each dose reconstruction.

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

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

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

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

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

3.1.1 Purpose

The purpose of this TBD is to describe the Pantex Plant occupational medical X-ray systems and practices. The Oak Ridge Associated Universities (ORAU) Team will use this information as needed to evaluate medical X-ray doses for EEOICPA claims.

3.1.2 Scope

Pantex operations have played an important role in the U.S. nuclear weapons program. Historically, Pantex provided several roles associated with the assembly, disassembly, retrofit, and modification of nuclear weapon systems (Mitchell 2003). Today, Pantex continues to fabricate high explosives and to assemble nuclear weapons. The principal operations at this site, however, are the dismantling of retired nuclear weapons and the maintenance of the nation's nuclear weapons stockpile. Pantex, which is operated by DOE's Office of Defense Programs, is the only facility in the United States that performs these operations.

The methods used for occupational medical X-rays have evolved since the beginning of Pantex operations. An objective of this document is to provide a technical basis to evaluate the dose received by workers from medical X-ray procedures. This document presents the organ doses from the screening medical procedures performed at Pantex for input to the NIOSH Interactive RadioEpidemiological Program (IREP).

3.2 EXAMINATION TYPES AND FREQUENCIES

Pantex required preemployment and routine physical examinations as part of its occupational health and safety program. The Medical Department maintains a log for each worker of what appears to be all X-ray examinations. An inspection of the logs for selected long-term workers showed that there was not a consistent pattern in the frequency of their examinations. Based on this inspection, practices apparently varied among workers, probably based on occupation and job responsibilities. Table 3-1 summarizes general patterns and default dose reconstruction recommendations.

Table 3-1. Pantex worker X-ray examinations.[a]

Period	Examination	Frequency	Default dose reconstruction recommendation
1952–1981	PA chest	For some workers, on employment and annual	Use log of X-ray examinations to identify occupation-related examinations for PA chest, AP lumbar spine, and LAT lumbar spine examinations. If log is not available in claim documentation, assume preemployment PA chest, AP lumbar spine, and LAT lumbar spine examinations and annual PA chest examinations.
	AP lumbar spine	For some workers, men only, preemployment	
	LAT lumbar spine	For some workers, men only, preemployment	
1982–2004	PA chest	For some workers, on employment and every 5 yr	Use log of X-ray examinations to identify occupation-related PA chest examinations. If log is not available in claim documentation, assume preemployment PA chest and a reexamination every 5 yr.

a. AP = anterior-posterior; LAT = lateral; PA = posterior-anterior.

3.3 EQUIPMENT AND TECHNIQUES

A complete history of Pantex X-ray equipment manufacturers, models, examination techniques, and exposure rates for these techniques has not been identified. Therefore, dose reconstruction must utilize assumptions favorable to claimants described in the latest revision of ORAUT (2005).

Section 3.6 summarizes the recommended approach for dose reconstructors. The following paragraphs summarize available historical information.

3.3.1 Photofluorography

This TBD analysis examined X-ray film records for long-term Pantex workers who began work in the early 1950s to determine if the Plant used photofluorography techniques for chest X-rays. All the records showed full-size 14- by 17-in. films for all years for which there were records, which include 1952, 1954 to 1956, 1958 to 1959, 1962, 1964 to 1966, 1968, 1970 to 1979, and 1982. These observations, along with conversations with Pantex employees, led to the conclusion that Pantex never used photofluorography.

3.3.2 X-Ray Machines

Historical records have been obtained for four X-ray machines at Pantex, as follows:

- **General Electric:** The earliest record found of a specific X-ray machine at Pantex involved a September 26, 1967, inspection, using Public Health Service Form 4495-3 (PHS 1967), of medical X-ray facilities. The inspector identified the control panel manufacturer and tube head manufacturer and model as General Electric, and identified the film as GAF Supreme with RADLIN T intensifying screens. Another survey of the medical X-ray facilities at Pantex occurred from August 13 to 18, 1970; the inspector found a General Electric control panel and a Profexray Model AZ Type 2 tube head (PHS 1970).

- **Picker:** From approximately July 11, 1972, to 1984, Pantex used a Picker X-Ray Pictronic 500 with a Picker X-Ray Style 2098 tube head. Half-value layer (HVL) measurements in 1972 were greater than 0.6 mm Al at 49 kVp and greater than 1.6 mm Al at 70 kVp (Alexander 1972a). In 1983, an evaluation of the actual number of pulses that occurred with different timer settings showed a variation from the time setting of –10% (at 0.5 s) to +33% (at 1/15 s) (Ikenberry 1983). Timer problems with this machine persisted through its replacement in the spring of 1984 (Ikenberry 1984). In 1983, HVL measurements were greater than 0.6 mm Al at 45 kVp, greater than 1.6 mm Al at 70 kVp, and greater than 2.6 mm Al at 90 kVp. Kodak BB-5 Blue brand film and DuPont Par screens were used (Ikenberry 1983).

- **Universal:** A Universal X-Ray control panel with a Eureka X-Ray Tube Company Model Sapphire 150 tube head was installed between March 19 and May 25, 1984. The unit was in service through at least November 1, 1993. All tested parameters were apparently excellent. HVL measurements were greater than 0.6 mm Al at 45 kVp, greater than 1.6 mm Al at 70 kVp, and greater than 2.6 mm Al at 90 kVp (Hill 1984). Kodak BB-5 Blue brand film and DuPont Par screens were used through 1990, after which DuPont Cronex 7 film was used with Cronex Quanta III screens (Kelly 1990). The first entrance skin exposure (ESE) for PA chest radiography was 4.4 mR measured on September 16, 1993, for a 23-cm-thick phantom at 192-cm source-to-image distance, 300 mA, and 72 kVp with a large focal spot and no grid (PHS 1993).

- **Continental:** A Continental TM-50 6626.235 X-ray machine was installed between November 1, 1993, and November 6, 1995. On November 6, 1995, several measurements of X-ray exposure at 30 in. for selected kVps between 60 and 100 in increments of 10 were performed (Huddleston 1995). For chest films, the measured value of 0.913 R for 100 mAs at 30 in. for 80 kVp was converted to the distance of 62 in. for a PA chest radiograph. The calculated value is 0.21 R for 100 mAs, and this value is equivalent to 0.02 cGy for the typical 10-mAs PA

chest examination. This machine uses *photo-timing*, which measures the incidence on the film directly during irradiation to determine the exposure time. This machine was in use as of June 2004 (Huddleston 1995).

There is evidence of ongoing Pantex reviews of the X-ray equipment and techniques (Gidley 1970; Alexander 1972b,c).

3.3.3 Specific Technique Charts

A table obtained from the Pantex Medical Department of suggested X-ray techniques by GE in 1941 (GE 1941) implies that Pantex probably used a GE CRT 1 or CRT 2 X-ray tube operated "on full wave rectification" with "fast" film in the early days. A 1967 table of desk instructions of X-ray examination steps (Pantex 1967) shows close similarity to the 1941 table. Measurements of the entrance kerma for the Pantex X-ray equipment and techniques have not been found for years before 1995 for the Continental X-ray machine. The entrance kerma calculated based on the information in the GE (1941) and Pantex (1967) technique charts, in addition to the measured beam output for the Continental system (Huddleston 1995), has been used in Tables 3-2, 3-3, and 3-4, which provide the technique factors for PA chest, AP lumbar spine, and LAT lumbar spine projections, respectively.

Table 3-2. Technique factors for PA chest X-rays.

Period	Total filtration (mm Al)	HVL (mm Al)	Current (mA)	Voltage (kVp)	Exposure time (s)	Entrance kerma (cGy)
Pre-1967	1.5	1.6[a]	200[b]	70	1/20	0.0256[c]
1967–1990	1.5	1.6[a]	100[d]	70	1/10	0.0256[c]
1991–2004	4.0	4.8[e]	Unknown	~80	(f)	0.0044[e]

a. 2.5-mm Al HVL was assumed for the determination of organ dose conversion factors (DCFs) using International Commission on Radiological Protection (ICRP) Publication 34 (ICRP 1982) as an assumption favorable to claimants. [1]
b. Based on X-ray techniques chart (GE 1941) corrected for 24-cm-thick individual.
c. Calculated based on information from NCRP (1989, Table B.3), and corrected to 1.5-mm Al equivalent filtration. [1]
d. Based on Pantex (1967) chart
e. Huddleston (1995). [2]
f. System has photo-timing; used 0.1 s and 100 mA in calculations of entrance kerma.

Table 3-3. Technique factors for AP lumbar spine X-rays.

Period	Total filtration (mm Al)	HVL (mm Al)	Current (mA)	Voltage (kVp)	Exposure time (s)	Entrance kerma (cGy)
Pre-1967–1981	1.5	1.6[a]	100[b]	70[b]	1[b]	1.34[c]
1982–2004	Not performed					

a. 2.5-mm Al HVL was assumed for the determination of organ DCFs using ICRP (1982) as an assumption favorable to claimants. [1]
b. Based on GE X-ray techniques chart (GE 1941) and Pantex technique chart (Pantex 1967) corrected for 24-cm-thick individual.
c. Calculated based on information from NCRP (1989, Table B.3) and corrected to 1.5-mm Al equivalent filtration. [2]

Table 3-4. Technique factors for LAT lumbar spine X-rays.

Period	Total filtration (mm Al)	HVL (mm Al)	Current (mA)	Voltage (kVp)	Exposure time (s)	Entrance kerma (cGy)
Pre-1967–1981	1.5	1.85[a]	100[b]	86[b]	2[b]	3.71[c]
1982–2004	Not performed					

a. 2.5-mm Al HVL was assumed for the determination of organ DCFs using ICRP (1982) as an assumption favorable to claimants. [1]
b. Based on GE X-ray techniques chart (GE 1941) and Pantex technique chart (Pantex 1967) corrected for 24-cm-thick individual.
c. Calculated based on information from NCRP (1989, Table B.3) and corrected to 1.5-mm Al equivalent filtration. [2]

3.4 ORGAN DOSE CALCULATIONS

Organ dose calculations for workers at Pantex from 1952 to the present involve three primary medical radiographic procedures administered in connection with preemployment and regular medical screening examinations:

- 14- by 17-in. PA chest film (preemployment and annual through 1981 and approximately every 5 yr thereafter)
- AP lumbar spine film (men only; preemployment only)
- LAT lumbar spine film (men only; preemployment only)

The analysis for this TBD evaluated only doses from these three techniques. Other radiographic examinations of Pantex employees that could have occurred are likely to be nonoccupational in the sense that they were associated with illness or injury and were not part of a routine screening process. There is no indication in the examined records that the occupational medical program routinely administered other radiographic examinations for screening. The analysis used the measurements performed for the Continental X-ray and techniques in 1995 (Huddleston 1995). This analysis assumed that an exposure of 1 R is equivalent to a kerma of 1 rad and to 10 mGy or 1 rem (ORAUT 2005). Tables 3-5 to 3-8 summarize organ doses for PA chest examinations for the various periods.

The purpose of preemployment AP and LAT lumbar spine examinations was to determine if individuals had preexisting back problems before hiring them for certain occupations. Little information has been found about these examinations. If there is not more specific information on the individual's log of worker X-ray examinations, dose reconstructors should use the assumption that AP and LAT lumbar spine examinations were conducted for each male worker employed before 1982 at preemployment only. Table 3-9 lists the organ doses for AP lumbar spine and LAT lumbar spine examinations. Pantex-specific documentation indicates the beam size for lumbar spine examinations was 12 inches, which indicates that collimation was used for these procedures (PHS 1967).

3.5 SKIN DOSE METHOD DESCRIPTION

Skin doses from AP chest projections are calculated differently dependent on proximity of the affected skin area to the primary beam. The following quantities are calculated: Primary beam entrance skin dose *ENSD*, primary beam exit skin dose *EXSD*, entrance skin dose outside but near the primary beam *ENSDNPB*, exit skin dose outside but near the primary beam *EXSDNPB*, and remote skin dose *RSD*.

ENSD is the product of *ESE* and a backscatter factor *BF* as shown in Equation 3-1. The *BF* is from Table B-8 of National Council on Radiation Protection and Measurements (NRCP) Report 102 (NCRP 1989) or from empirical data. This dose applies to all skin surfaces in the beam on the entrance side of the body. For collimated PA chest projections this includes the skin of the back, neck, and shoulders. For uncollimated PA chest projections this includes the skin of the back, neck, shoulders, back of the head, ears, upper arms, elbows, lower arms, and buttocks.

$$ENSD = ESE \times BF \quad (3\text{-}1)$$

Table 3-5. Calculated organ dose for PA chest X-rays before 1967 assuming minimal collimation.

Organ	DCF (mGy/Gy air kerma) (beam quality for 2.5-mm Al HVL)[a]	Organ dose (rem)
Thyroid[b]	174	4.45E-03
Eye/brain[c]	174	4.45E-03
Ovaries[d]	168	4.30E-03
Urinary bladder	168	4.30E-03
Colon/rectum	168	4.30E-03
Testes	9.1	2.30E-04
Lungs	451	1.15E-02
Thymus	451	1.15E-02
Esophagus	451	1.15E-02
Stomach	451	1.15E-02
Bone surfaces	451	1.15E-02
Liver/gall bladder/spleen	451	1.15E-02
Remainder	451	1.15E-02
Female breast	49	1.25E-03
Uterus[e]	149	3.81E-03
Bone marrow	92	2.36E-03
Entrance skin dose in primary beam[f]	N/A	3.46E-02
Exit skin dose in primary beam[g]	N/A	8.60E-04
Entrance skin dose near but outside primary beam[g]	N/A	3.46E-03
Exit skin dose near but outside primary beam[g]	N/A	8.60E-05
Remote skin dose–thighs to knees[g]	N/A	9.91E-06
Remote skin dose–knees to ankles[g]	N/A	3.62E-06
Remote skin dose–ankles[g]	N/A	1.64E-06

a. DCFs from ICRP (1982, Tables A.2 to A.8); N/A = not applicable. [1]
b. The DCF for the thyroid is based on ICRP (1982, Table A.2) for a cervical spine procedure and a depth dose correction factor of 0.2. [1]
c. The DCF for the eye/brain is based on the thyroid in ICRP (1982, Table A.2) for a cervical spine procedure and a depth dose correction factor of 0.2. [1]
d. The DCF for the ovaries is based on ICRP (1982, Table A.3) for an abdominal procedure. [1]
e. The DCF for the uterus is based on ICRP (1982, Table A.7) for an abdominal procedure. [1]
f. Skin dose was determined by multiplying ESE by a backscatter of 1.35 for an HVL of 2.5 mm Al. From NCRP (1989, Table B-8). [1]
g. Calculated based on Section 3.5. [3]

EXSD is the *ENSD* divided by an adjusted absorption factor *AFF*, which is the absorption factor for a 23-cm chest or 23-cm abdomen tabulated in Table B.7 of NCRP Report 102 (NCRP 1989) decreased by 10% as shown in Equations 3-2 and 3-3; this factor is favorable to claimants. This dose applies to all skin surfaces in the beam on the exit side of the body. For collimated PA chest projections this includes the skin of the chest, neck, front side of the shoulders, and upper abdomen. For uncollimated PA chest projections this includes the skin of the chest, neck, front side of the shoulders, upper abdomen, lower abdomen and face.

$$EXSD = ENSD \Big/ AFF \tag{3-2}$$

$$AFF = AF \times 0.9 \tag{3-3}$$

Table 3-6. Calculated organ dose for PA chest X-rays, 1967 to 1971.

Organ	DCF (mGy/Gy air kerma) (beam quality for 2.5-mm Al HVL)[a]	Organ dose (rem)
Thyroid[b]	174	4.45E-03
Eye/brain[c]	174	4.45E-03
Ovaries[d]	168	4.30E-03
Urinary bladder	168	4.30E-03
Colon/rectum	168	4.30E-03
Testes	9.1	2.30E-04
Lungs	451	1.15E-02
Thymus	451	1.15E-02
Esophagus	451	1.15E-02
Stomach	451	1.15E-02
Bone surfaces	451	1.15E-02
Liver/gall bladder/spleen	451	1.15E-02
Remainder	451	1.15E-02
Female breast	49	1.25E-03
Uterus[e]	149	3.81E-03
Bone marrow	92	2.36E-03
Entrance skin dose in primary beam[f]	N/A	3.46E-02
Exit skin dose in primary beam[g]	N/A	8.60E-04
Entrance skin dose near but outside primary beam[g]	N/A	3.46E-03
Exit skin dose near but outside primary beam[g]	N/A	8.60E-05
Remote skin dose–thighs to knees[g]	N/A	9.91E-06
Remote skin dose–knees to ankles[g]	N/A	3.62E-06
Remote skin dose–ankles[g]	N/A	1.64E-06

a. DCFs from ICRP (1982, Tables A.2 to A.8); N/A = not applicable. [1]
b. The DCF for the thyroid is based on ICRP (1982, Table A.2) for a cervical spine procedure and a depth dose correction factor of 0.2. [1]
c. The DCF for the eye/brain is based on the thyroid in ICRP (1982, Table A.2) for a cervical spine procedure and a depth dose correction factor of 0.2. [1]
d. The DCF for the ovaries is based on ICRP (1982, Table A.3) for an abdominal procedure. [1]
e. The DCF for the uterus is based on ICRP (1982, Table A.7) for an abdominal procedure. [1]
f. Skin dose was determined by multiplying ESE by a backscatter of 1.35 for an HVL of 2.5 mm Al. From NCRP (1989, Table B-8). [1]
g. Calculated based on Section 3.5. [3]

ENSDNPB is 10% of the *ENSD* as shown in Equation 3-4. This equation is assumed based on a tabulated value in International Commission on Radiological Protection (ICRP) Publication 34 that shows that testes dose is 10% of the central beam dose when the testes are just outside the primary beam (ICRP 1982).

$$ENSDNPB = ENSD \times 0.1 \quad (3\text{-}4)$$

EXSDNPB is similarly 10% of the *EXSD* as shown in Equation 3-5.

$$EXSDNPB = EXSD \times 0.1 \quad (3\text{-}5)$$

RSD, shown in Equation 3-6, is a function of:

- *ENSD*
- Inverse square of the distance *R* from the center of the primary beam to nearest point on the skin surface of interest

Table 3-7. Calculated organ doses for PA chest X-rays, 1972 to 1990.

Organ	DCF (mGy/Gy air kerma) (beam quality for 2.5-mm Al HVL)[a]	Organ dose (rem)
Thyroid	32	8.19E-04
Eye/brain	32	8.19E-04
Ovaries	1	2.56E-05
Urinary bladder	1	2.56E-05
Colon/rectum	1	2.56E-05
Testes	0.01	2.56E-07
Lungs	451	1.15E-02
Thymus	451	1.15E-02
Esophagus	451	1.15E-02
Stomach	451	1.15E-02
Bone surfaces	451	1.15E-02
Liver/gall bladder/spleen	451	1.15E-02
Remainder	451	1.15E-02
Female breast	49	1.25E-03
Uterus	1.3	3.33E-05
Bone marrow	92	2.36E-03
Entrance skin dose in primary beam[b]	N/A	3.46E-02
Exit skin dose in primary beam[c]	N/A	8.60E-04
Entrance skin dose near but outside primary beam[c]	N/A	3.46E-03
Exit skin dose near but outside primary beam[c]	N/A	8.60E-05
Remote skin dose–thighs to knees[c]	N/A	9.91E-06
Remote skin dose–knees to ankles[c]	N/A	3.62E-06
Remote skin dose–ankles[c]	N/A	1.64E-06

a. DCFs from ICRP (1982, Tables A.2 to A.8); N/A = not applicable. [1]
b. Skin dose was determined by multiplying ESE by a backscatter of 1.35 for an HVL of 2.5 mm Al. From NCRP (1989, Table B-8). [1]
c. Calculated based on Section 3.5. [3]

- A ratio of scattered to incident exposure equal to 0.0005 based on the exposure at 1 m due to 90° scattering of 70-kVp radiation in accordance with Table B-2 of NCRP Report 49 (NCRP 1976)

- Average percent depth dose *ADD* at the midpoint of a 23-cm torso (rounded to 12 cm to match the nearest tabulated value and to ensure bias favorable to claimants) based on the HVL of the beam as tabulated in NCRP Report 102 (NCRP 1989, Table B.8) for the PA chest and AP lumbar spine procedures

- Average percent depth dose *ADD* at the midpoint of a 35-cm torso (rounded to 16 cm to match the nearest tabulated value and to ensure bias favorable to claimants) based on the HVL of the beam as tabulated in NCRP Report 102 (NCRP 1989, Table B.8) for the LAT lumbar spine procedures

- A bias factor favorable to claimants of 1.1 to allow for 10% uncertainty in tabulated values of *ADD*

$$RSD = ENSD \times 0.0005 \times ADD \times 1.1 \times \left(\frac{1}{R}\right)^2 \quad (3\text{-}6)$$

Table 3-8. Calculated organ doses for PA chest X-rays, 1991 to 2004.

Organ	DCF (mGy/Gy air kerma) (beam quality for 5.0-mm Al HVL)[a]	Organ dose (rem)
Thyroid	110	4.84E-04
Eye/brain	110	4.84E-04
Ovaries	13.2	5.81E-05
Urinary bladder	13.2	5.81E-05
Colon/rectum	13.2	5.81E-05
Testes	0.01	4.40E-08
Lungs	802	3.53E-03
Thymus	802	3.53E-03
Esophagus	802	3.53E-03
Stomach	802	3.53E-03
Bone surfaces	802	3.53E-03
Liver/gall bladder/spleen	802	3.53E-03
Remainder	802	3.53E-03
Female breast	166	7.30E-04
Uterus	11.2	4.93E-05
Bone marrow	258	1.14E-03
Entrance skin dose in primary beam[b]	N/A	6. 60E-03
Exit skin dose in primary beam[c]	N/A	3.31E-04
Entrance skin dose near but outside primary beam[c]	N/A	6.60E-04
Exit skin dose near but outside primary beam[c]	N/A	3.31E-05
Remote skin dose–thighs to knees[c]	N/A	3.03E-06
Remote skin dose–knees to ankles[c]	N/A	1.11E-06
Remote skin dose–ankles[c]	N/A	5.01E-07

a. DCFs extrapolated from ICRP (1982, Tables A.2 to A.8) extrapolated to 5.0 mm Al HVL; N/A = not applicable. [2]
b. Skin dose was determined by multiplying ESE by a backscatter of 1.5 for an HVL of 5.0 mm Al. Extrapolated based on information from NCRP (1989, Table B-8). [2]
c. Calculated based on Section 3.5. [3]

The distances used for calculation of the *RSD* for the PA chest X-ray procedures were:

- Thighs to knees – 0.52 m
- Knees to ankles – 0.86 m
- Ankles – 1.28 m

The distances used for calculation of the *RSD* for the AP and LAT lumbar-spine procedures were:

- Thighs to knees – 0.26 m
- Knees to ankles – 0.60 m
- Ankles – 1.02 m

3.6 UNCERTAINTY ANALYSIS

The description of error and uncertainty in ORAUT (2005) is directly applicable to the evaluation of medical X-ray doses to Pantex workers. Available historical documentation is sufficient to ensure analysis of the dose that is favorable to claimants. Dose reconstructors should use the recommendation from ORAUT (2005) to assume that errors are all positive (i.e., only +30%) for Pantex workers.

Table 3-9. Organ dose estimates for lumbar spine AP and LAT X-rays before January 1, 1982.

Organ	View	DCF (mGy/Gy air kerma) (beam quality for 2.5 mm Al HVL)[a]	Organ dose (rem)
Thyroid	AP	0.3	4.02E-04
	LAT	0.01	3.71E-05
Eye/brain	AP	0.3	4.02E-04
	LAT	0.01	3.71E-05
Ovaries	AP	216	2.89E-01
	LAT	47	1.74E-01
Urinary bladder	AP	216	2.89E-01
	LAT	47	1.74E-01
Colon/rectum	AP	216	2.89E-01
	LAT	47	1.74E-01
Testes[b]	AP	18	2.41E-02
	LAT	3.3	1.22E-02
Lungs	AP	79	1.06E-01
	LAT	14	5.19E-02
Thymus	AP	79	1.06E-01
	LAT	14	5.19E-02
Esophagus	AP	79	1.06E-01
	LAT	14	5.19E-02
Stomach	AP	79	1.06E-01
	LAT	14	5.19E-02
Bone surfaces	AP	79	1.06E-01
	LAT	14	5.19E-02
Liver/gall bladder/spleen	AP	79	1.06E-01
	LAT	14	5.19E-02
Remainder	AP	79	1.06E-01
	LAT	14	5.19E-02
Breast[c]	AP	25	3.35E-02
	LAT	13	4.82E-02
Uterus	AP	287	3.85E-01
	LAT	31	1.15E-01
Bone marrow	AP	37	4.96E-02
	LAT	22	8.16E-02
Entrance skin dose in primary beam[d]	AP	N/A	1.81E+00
	LAT	N/A	5.01E+00
Exit skin dose in primary beam[e]	AP	N/A	4.50E-02
	LAT	N/A	1.95E-01
Entrance skin dose near but outside primary beam[e]	AP	N/A	1.81E-01
	LAT	N/A	5.01E-01
Exit skin dose near but outside primary beam[e]	AP	N/A	4.50E-03
	LAT	N/A	1.95E-02
Remote skin dose–thighs to knees[e]	AP	N/A	2.08E.03
	LAT	N/A	3.06E-03
Remote skin dose–knees to ankles[e]	AP	N/A	3.90E-04
	LAT	N/A	5.74E-04
Remote skin dose–ankles[e]	AP	N/A	1.35E-04
	LAT	N/A	1.99E-04

a. DCFs from ICRP (1982, Tables A.2 to A.8); N/A = not applicable. [1]
b. DCFs based on abdominal projection from ICRP (1982, Table A.4). [1]
c. DCFs based on upper gastrointestinal projection from ICRP (1982, Table A.6). [1]
d. Dose based on multiplying entrance kerma by a backscatter of 1.35 for an HVL of 2.5 mm Al; from NCRP (1989, Table B-8). [1]
e. Calculated based on Section 3.5. [3]

3.7 INSTRUCTION GUIDE FOR DOSE RECONSTRUCTORS

Pantex practice involved maintaining a log of the date and type of medical examination and a historical record of the associated radiographs. DOE-provided medical X-ray information should include a copy or transcription of information from this log. Dose reconstructors should use the list of examinations in this log. In the event that the log is not available, dose reconstructors should use the default assumptions in Table 3-10 to ensure an assessment of dose favorable to the claimant.

Table 3-10. Summary of dose reconstruction recommendations.

Examination	Period	Default frequency	Table
PA chest	Before 1/1/1967	Preemployment and annually thereafter	Table 3-5
	1/1/67–12/31/71		Table 3-6
	1/1/72–12/31/81		Table 3-7
	1/1/82–12/31/90	Preemployment and every 5 yr thereafter	Table 3-7
	1/1/91–2004		Table 3-8
Lumbar spine AP	Before 1/1/1982	Preemployment, men only	Table 3-9
Lumbar spine LAT		Preemployment, men only	Table 3-9

For actual dose calculations, dose reconstructors should assume a normal distribution with an uncertainty of ±30% at the 99% confidence interval. However, to select judgments favorable to claimants, dose reconstructors should use only the positive uncertainty and multiply the doses listed in Tables 3-5 to 3-9 by a factor of 1.3 to include uncertainty at the 99% confidence level (ORAUT 2005).

3.8 ATTRIBUTIONS AND ANNOTATIONS

Where appropriate in the preceding text, bracketed callouts have been inserted to indicate information, conclusions, and recommendations provided to assist in the process of worker dose reconstruction. These callouts are listed in this section with information provided to identify the source and justification for each associated item. Conventional references are provided in the next section that link data, quotations, and other information to documents available for review on the ORAU Team servers.

[1] Winslow, Robert C., CHP. Dade Moeller & Associates. Senior Health Physicist. August 2006. The information provided in the referenced documents for Pantex is adequate to calculate doses that could have been received during occupationally required medical X-ray procedures. However, there is some uncertainty associated with how measurements to determine the total filtration values were performed during this time. Therefore, an approach that is favorable to the claimants was used for this TBD. This approach included the calculation of the entrance kerma based on information provided in NCRP (1989, Table B.3) for the given kVp and a distance of 183 cm that was then corrected based on an assumed chest size of 24 cm plus 5 cm between the chest and film using the inverse square law for point sources. This value was then corrected based on the provided current and exposure times. NCRP (1989, Table B.3) provides information based on a total filtration of 2.5 mm Al. This was adjusted to account for the stated 1.5 mm Al based on the following formula where t is the thickness of aluminum in millimeters and I and I_o are the beam intensities with and without the filter, respectively:

$$I = I_o e^{-0.5t}$$

Given the uncertainty associated with measurements to determine the total filtration values, an assumption was made to apply DCFs based on 2.5-mm Al HVL in ICRP (1982), which is also favorable to claimants.

[2] Winslow, Robert C., CHP. Dade Moeller & Associates. Senior Health Physicist. August 2006. Information in site documentation (Huddleston 1995) indicates that an HVL of 4.8 mm Al was in place on the X-ray machine that was used starting in 1991. ICRP (1982) and NCRP (1989) provide information only up to 4 mm Al HVL. Therefore, an extrapolation was performed for 5-mm Al HVL to determine the factors used to convert the entrance kerma to absorbed dose for the various organs and the backscatter factor for the entrance skin dose.

[3] Winslow, Robert C., CHP. Dade Moeller & Associates. Senior Health Physicist. August 2006. The determination of the absorption factor used in the calculations for the exit skin dose was based on an assumed thickness of overlying tissue to exit surface of 23 cm. Before 1991, an HVL of 2.5 mm Al was used, and the value was interpolated based on the values provided for 2 and 3 mm Al. For 1991 to 2004, the value provided for 5-mm Al HVL was used as an assumption favorable to claimants.

REFERENCES

Alexander, R. E., 1972a, "Diagnostic X-ray Machine – Building 12-2 Medical," memorandum to F. J. Kelly (Pantex Medical Director), Mason & Hanger-Silas Mason Company, Pantex Plant, Amarillo, Texas, October 17.

Alexander, R. E., 1972b, "X-ray Machine, 12-2 Medical," memorandum to F. J. Kelly (Pantex Medical Director), Mason & Hanger-Silas Mason Company, Pantex Plant, Amarillo, Texas, February 10.

Alexander, R. E., 1972c, "X-ray Installation 12-2 Medical," memorandum to F. J. Kelly (Pantex Medical Director), Mason & Hanger-Silas Mason Company, Pantex Plant, Amarillo, Texas, July 7.

GE (General Electric Company), 1941, "Technic Chart," General Electric X-Ray Corporation, Milwaukee, Wisconsin, copy obtained from Mason & Hanger-Silas Mason Company, Pantex Plant, Amarillo, Texas.

Gidley, M. D., 1970, memorandum to F. J. Kelley (Pantex Medical Director), Mason & Hanger-Silas Mason Company, Pantex Plant, Amarillo, Texas, August 19.

Hill, L. G., 1984, "Diagnostic X-ray Machine," memorandum to F. J. Kelly (Pantex Medical Director), Mason & Hanger-Silas Mason Company, Pantex Plant, Amarillo, Texas, May 25.

Huddleston, A. L., 1995, letter to N. Bryson (Mason and Hanger-Silas Mason Company), Texas Radiation Physics Associates, Dallas, Texas, December 12.

ICRP (International Commission on Radiological Protection), 1982, *Protection of the Worker in Diagnostic Radiology*, Publication 34, Pergamon Press, Oxford, England.

Ikenberry, T. A. 1983, "Diagnostic X-ray Machine," memorandum to F. J. Kelly (Pantex Medical Director), Mason & Hanger-Silas Mason Company, Pantex Plant, Amarillo, Texas, March 16.

Ikenberry, T. A. 1984, "Diagnostic X-ray Machine, Bldg. 12-2, Medical," memorandum to F. J. Kelly (Pantex Medical Director), Mason & Hanger-Silas Mason Company, Pantex Plant, Amarillo, Texas, March 19.

Kelly, T. J., 1990, "Diagnostic X-ray Machine," memorandum to C. M. Lang (Pantex Medical Director), Mason & Hanger-Silas Mason Company, Pantex Plant, Amarillo, Texas, June 22.

Mitchell, K. C., 2003, *Rhetoric to Reality: A Cold War Context Statement for the Pantex Plant*, 1951 – 1991, BWXT Pantex LLC, Pantex Plant, Amarillo, Texas.

NCRP (National Council on Radiation Protection and Measurements), 1976*, Structural Shielding Design and Evaluation for Medical Use of X-rays and Gamma Rays of Energies up to 10 MeV,* Report 49, Bethesda, Maryland.

NCRP (National Council on Radiation Protection and Measurements), 1989*, Medical X-Ray Electron Beam and Gamma-Ray Protection for Energies Up to 50 MeV (Equipment Design, Performance and Use),* Report 102, Bethesda, Maryland.

ORAUT (Oak Ridge Associated Universities Team), 2005, *Dose Reconstruction from Occupationally Related Diagnostic X-Ray Procedures,* ORAUT-OTIB-0006, Rev. 03 PC-1, Oak Ridge, Tennessee, December 21.

Pantex, 1967, "X-Ray Procedures," desk instructions dated April 5 and April 10, initialed by CS, Mason & Hanger-Silas Mason Company, Pantex Plant, Amarillo, Texas.

PHS (Public Health Service), 1967, "X-Ray Protection Survey Report, Pantex Medical Department, Building 12-36," Form PHS-4495-3 (Rev. 7-65), Mason & Hanger-Silas Mason Co., Inc., Amarillo, Texas, September 26.

PHS (Public Health Service), 1970, "X-Ray Protection Survey Report, Pantex Medical Department, Building 12-2," Form PHS-4495-3 (Rev. 7-65), Mason & Hanger-Silas Mason Co., Inc., Amarillo, Texas, August 18.

PHS (Public Health Service), 1993, "Comprehensive Radiation Protection Survey of Mason & Hanger-Pantex Central Health Facility, Bldg 12-2," Mason & Hanger-Silas, Mason Co., Inc., Amarillo, Texas, November 1.

GLOSSARY

absorbed dose
The energy imparted per unit mass by ionizing radiation to matter at a specified point. The International System unit of absorbed dose is joules per kilogram. The special name for this unit is the gray (Gy). The previously used special unit of absorbed dose, rad, is being replaced by the gray (1 rad = 0.01 Gy; 1 Gy = 100 rad).

anterior-posterior (AP)
Physical orientation of the body relative to a penetrating directional radiation field such that the radiation passes through the body from the front to the back.

entrance kerma
Air kerma in air without backscatter at the point of entry into the body. Also called entrance kerma, and formerly called *entrance skin exposure*.

entrance skin exposure (ESE)
Air kerma in air without backscatter at the point of entry into the body. The ESE is measured in units of Roentgen (R) or kerma (Gy). Also called entrance kerma.

filtration
The process of filtering an X-ray beam, usually with millimeter thicknesses of aluminum material between the X-ray source and the film that preferentially absorbs photons from the beam. Usually measured in equivalent millimeters of aluminum.

half-value layer (HVL)
Thickness of a specified substance, usually specified in equivalent millimeters of aluminum, that filters an X-ray beam to reduce the kerma rate by one-half.

kerma
Measure in units of absorbed dose (usually grays but sometimes rads) of the energy released by radiation from a given amount of a substance. Kerma is the sum of the initial kinetic energies of all the charged ionizing particles liberated by uncharged ionizing particles (neutrons and photons) per unit mass of a specified material. Free-in-air kerma refers to the amount of radiation at a location before adjustment for any external shielding from structures or terrain. The word derives from kinetic energy released per unit mass.

lateral (LAT)
Orientation of the body during an X-ray procedure in which the X-rays pass from one side of the body to the other.

photofluorography
Historical radiographic technique used for cost- and time-effective production of chest images for screening a large number of people in a short period. The X-ray image produced on a fluorescent screen was photographed on 4inch by 5inch film. Photofluorography was the primary method of screening large populations for tuberculosis before the advent of nonradiographic tuberculosis screening methods. Also called mass miniature radiography. Not to be confused with fluoroscopy.

posterior-anterior (PA)

Physical orientation of the body relative to a penetrating directional radiation field such that the radiation passes through the body from the back to the front.

radiography

The process of producing images on film (or other media) with radiation. Production of radiographs.

roentgen (R)

Unit of photon (gamma or X-ray) exposure for which the resultant ionization liberates a positive or negative charge equal to 2.58×10^{-4} coulombs per kilogram (or 1 electrostatic unit of electricity per cubic centimeter) of dry air at 0°C and standard atmospheric pressure. An exposure of 1 R is approximately equivalent to an absorbed dose of 1 rad in soft tissue for higher energy photons (generally greater than 100 kiloelectron-volts).

rem

Traditional unit of radiation dose equivalent that indicates the biological damage caused by radiation equivalent to that caused by 1 rad of high-penetration X-rays multiplied by a quality factor. The average American receives 360 millirem a year from background radiation. The sievert is the International System unit; 1 rem equals 0.01 sievert. The word derives from roentgen equivalent in man; rem is also the plural.

technique or technic

Combination of X-ray machine settings used to produce radiographs consisting of the applied kilovoltage (kVp), tube current (milliamperes), and exposure time (seconds). The last two parameters are often multiplied to yield the electric charge that has crossed the X-ray tube during the exposure in units of milliampere-seconds (mAs). Any combination of time and tube current that produces a given product in milliampere-seconds produces the same exposure for a fixed peak kilovoltage.

X-ray

Electromagnetic radiation (photons) produced by bombardment of atoms by accelerated particles. X-rays are produced by various mechanisms including bremsstrahlung and electron shell transitions within atoms (characteristic X-rays).