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PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
02/09/2004	00	New Technical Basis Document for the Rocky Flats Plant – Occupational Medical Dose. First approved issue. Initiated by Robert Meyer.
04/23/2007	01	Approved Revision 01 initiated to revise Table 3.4.2-2 (now Table 3-6), text, and dose estimate tables to be consistent with ORAUT-OTIB-0006 Rev 03 PC-1. Revised Table 3.2-1 (now Table 3-1) and text to specify the inclusion of termination X-rays for the period of 1952-1986. Revised Table 3.4.1-2 (now Table 3-5) per commitment tracking form dated 02/06/2006. Revised to include attribution information per ORAU direction. The Worker Outreach comment from CT-0203 was addressed. Worker outreach comment from the June 23, 2004, meeting of the United Steelworkers of America Local 8031 and Rocky Flats Security Officers Local Union 1 was addressed in Section 3.1. Incorporates formal internal and NIOSH review comments. Constitutes a total rewrite of document. This revision results in an increase in assigned dose and a PER is required. Training required: As determined by the Task Manager. Initiated by Robert Meyer.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS AND ABBREVIATIONS

AP	anterior-posterior
CFR	Code of Federal Regulations
cGy	centigray
cm	centimeter
DOE	U.S. Department of Energy
EEOICPA	Energy Employees Occupational Illness Compensation Program Act
ESE	entrance skin exposure
Gy	gray
HVL	half-value layer
ICRP	International Commission on Radiological Protection
in.	inch
IREP	Interactive RadioEpidemiological Program
kerma	kinetic energy released per unit mass
keV	kiloelectron-volt, 1,000 electron-volts
kg	kilogram
kV	kilovolt
kVp	kilovolts-peak, applied kilovoltage
LAT	lateral
m	meter
mA	milliampere
mAs	milliampere-second
mGy	milligray
mm	millimeter
NIOSH	National Institute for Occupational Safety and Health
ORISE	Oak Ridge Institute for Science and Education
PA	posterior-anterior
PFG	photofluorography
POC	probability of causation
R	roentgen
RFP	Rocky Flats Plant
s	second
SI	International System of Units
SID	source-to-image distance
SSD	source-to-skin distance
Sv	sievert
TBD	technical basis document
TIB	technical information bulletin

U.S.C.	United States Code
yr	year
§	section or sections

3.1 INTRODUCTION

3.1.1 Purpose

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

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

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

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

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

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

3.1.2 Scope

The following sections describe the methodology used to estimate absorbed dose from X-ray exposure for Rocky Flats Plant (RFP) workers. Where data are unavailable, the assumptions made are favorable to claimants [1]. Section 3.1 provides introductory text. Section 3.2 describes X-ray examination frequency at RFP. Section 3.3 provides information on equipment and techniques used at RFP, including assumptions necessitated by lack of protocol, measurement, or records data. Section 3.4 provides organ dose estimates by calendar year and type of X-ray. Section 3.5 documents uncertainties.

3.2 BACKGROUND

As part of the requirements for employment at RFP, entrance, exit, and periodic physical examinations were performed on all employees. These physical examinations included radiographic examinations of the lungs and, for some employees, the lumbar spine [2]. 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). Only medical exposures that were required as a condition of employment are included; diagnostic and therapeutic procedures not required for employment are excluded (e.g., exposures received in the treatment of work-related injuries).

As described in International Commission on Radiological Protection (ICRP) Publication 34, *Protection of the Patient in Diagnostic Radiology*, the amount of energy absorbed in the body and its distribution in specific organs can be determined by measurement or calculation (ICRP 1982). Absorbed dose in tissue, measured in units of gray, is equal to the energy absorbed per unit mass at a point in the human body. The quantity of radiation in terms of exposure from ionization of a specific mass of air by X-rays was in previous years measured in roentgens. The current International System of Units (SI) expresses this quantity in *air kerma* (kerma derives from kinetic energy released per unit mass). An exposure of 1 R corresponds to an air kerma of 8.7 mGy.

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 guidelines (NIOSH 2002) is:

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

where

D_{om} = occupational medical dose
n = number of examinations in a calendar year
Di = 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 no information is known about the energy spectra, values should conservatively be assumed to be in the 30- to- 250-kV photon range (which is favorable to claimants). The guidelines also state that the uncertainty distribution about each X-ray procedure is assumed to follow a normal distribution, with D_{om} being the mean dose.

3.3 EXAMINATION FREQUENCY

The frequency of X-ray examinations varied significantly for RFP workers (Table 3-1). A protocol for frequency of a single posterior-anterior (PA) view chest X-ray as a function of job category was not established until approximately 1986. After that date, the frequency of routine chest X-rays varied widely: None for office personnel, every 5 yr for respirator wearers, and annually for beryllium and asbestos workers over age 45 and with a 10-yr history of asbestos exposure (RFP 1991). Before approximately 1986, many production workers would receive single-view chest X-rays on a nearly annual basis. (In a sample of medical records of production workers, no one was found to have consistently received annual chest X-rays due to occasional missed examinations and periods when examinations were apparently not provided on an annual basis [3].) Inspection of medical records has not revealed any more specific designation of X-ray protocol by worker classification or job description [4]. Based on the records reviewed during preparation of this document, no worker received such examinations more often than annually [5]. Termination chest X-rays are also recommended for the period 1952 to 1985 because they were common at other DOE sites and the RFP protocol for this period has not been found [6]. Termination X-rays are believed by former medical workers to have been uncommon at RFP [7].

Table 3-1. X-ray examination frequencies.

Period	Frequency	View	Comment
1986–present	Annually	Chest (PA)	Beryllium workers; asbestos workers over age 45 with 10-yr work history exposure to asbestos (RFP 1991)
	Every 5th yr	Chest (PA)	Respirator wearers (RFP 1991)
	None	Chest (PA)	Office personnel (RFP 1991)
1952–1985	Annual and termination	Chest (PA)	All workers[a]
1952–1968	Annual	Chest (PFG)	All workers[a]
1952–1974	Once	Lumbar (AP and LAT)	All workers

a. Assumed all workers received X-rays because protocol has not been found [8]. Production workers were known to receive annual chest X-ray examinations; this protocol is assumed to have occurred for all years [9].

Between 1952 and 1974, all workers received spinal X-rays during their initial employment (prehire) medical examination. This X-ray series consisted of a 14- by 17-in. anterior-posterior (AP) view and a 10- by 12-in. lateral (LAT) view of the lumbosacral spine [9].

Without a review of the specific energy employee's X-ray file (stored at the Denver Federal Center), an exact count of the X-rays is impossible. The medical files (also stored at the Denver Federal Center) did not always document each X-ray taken, at least not in the years before the mid-1970s [10]. An approach to the estimation of the X-rays taken that is favorable to claimants would therefore assume lumbosacral spine X-rays were taken if the energy employee started work between 1952 and 1974. If an annual single-view chest X-ray is also assumed, this potential overestimation of X-ray use would compensate for the few repeat radiographs taken because of poor quality of the initial X-ray [11].

3.4 EQUIPMENT AND TECHNIQUES

Although RFP radiological practices are assumed to have followed standards of medical practice to minimize dose to the workers, the type of equipment, technique factors, and machine calibrations are not fully known for years before 2001. Members of the RFP TBD team interviewed Medical and Records group personnel and Colorado Department of Public Health and Environment personnel and determined that X-ray machine records for equipment in use before 2001 are not readily available [12]. However, some information has been found related to equipment type and ratings; these data

have been used in conjunction with default data where needed to provide estimates of potential exposure that are favorable to claimants. Individual medical records should contain notations about dates and purposes of X-ray examinations, but reviews of medical records showed that this was not always the case before the mid-1970s [13].

X-ray organ dose estimates for occupational X-rays administered at RFP are provided here for known equipment (Type I – June 11, 2001, to present) and default estimates are provided for earlier periods (ORAUT 2005). The use of proxy data is based on the belief that RFP, like other DOE sites, used the standard radiological procedures of the time. All assumptions made were conservative (favorable to claimants). The default dose estimates are from the Technical Information Bulletin (TIB) *Dose Reconstruction from Occupationally Related Diagnostic X-ray Procedures* (ORAUT 2005) for chest and lumbar spine X-rays.

Photofluorography (PFG) could have been performed at RFP. While no specific records or protocols have been found in relation to PFG at RFP, a note indicating that a fluoroscope was removed from the Plant in 1968 indicates that fluoroscopy could have been performed (Dean 2003), and workers recall that a "portable x-ray machine" was used. Therefore, it has been assumed that PFG could have been performed. Fluoroscopic equipment is different from photofluorographic equipment and was not generally of much use for occupational medical examinations that would have been performed (ORAUT 2005). However, because no further site-specific information has been found, and considering the uncertainty related to PFG use and input from former workers, default estimates of PFG exposure from ORAUT (2005) have been recommended in this TBD if any evidence of PFG use is found in individual claim files.

Efforts will continue to find all related information for RFP. However, until more accurate records are found, these assumptions provide estimates for medical X-ray exposure that are favorable to claimants.

Tables 3-2 and 3-3 summarize known information regarding equipment and techniques.

Table 3-2. Description of X-ray equipment used at RFP and proxy information.

Classification	Period	Equipment	Source
Type I	June 11, 2001–present	Hologic/BXT202W	Dean 2003 [13]
Type II	May 29, 1987–March 6, 2001	Eureka XMA tube; Generator unknown	Dean 2003 [13]
Type III	September 1, 1976–May 28, 1987	Generator unknown; Victoreen R Meter; BRH test stand; X-ray Timer; Aluminum Filter set; light meter	Dean 2003
Type IV	July 1953–August 30,1976	Keleket	Dean 2003

Table 3-3. Equipment settings and ratings (Dean 2003).

Machine	Period	View	Current (mA)	Voltage (kVp)	Exposure time(s)
Type I[a]	6/11/2001–present	Chest PA	300	110	0.003
Type II[b]	5/29/1987–3/6/2001	Chest PA	360	130	Unknown
Type III[b]	9/01/1976–5/28/1987	Chest PA	Unknown	80	Unknown
Type IV[b]	7/1953–8/30/1976	Chest PA	200	140	Unknown
	1952–1974	Lumbar AP[c]	200	140	Unknown
	1952–1974	Lumbar LAT[c]	200	140	Unknown

a. Typical setting varied from 0.8 mAs for an average-sized person to 2.3 mAs for a very large person; 2.3 mA was used to be conservative.
b. Maximum machine ratings (Dean 2003); data not used to calculate doses, but are presented for informational purposes.
c. Performed only from 1952 to 1974 [14]; settings are maximum machine ratings (Dean 2003).

3.5 ORGAN DOSE ESTIMATES

Organ dose estimates are provided in this section. Section 3.5.1 describes the methodology used to estimate these doses; Section 3.5.2 discusses the results.

3.5.1 Parameters and Estimation Method

The ICRP (1982) guidance uses the following parameters to estimate air kerma and absorbed dose:

1. Source-to-image distance (SID) in centimeters
2. Total filtration (millimeters of aluminum)
3. Estimate of person thickness (AP and LAT)
4. Machine settings (mAs, kVp, film size, and single-phase or three-phase)

If measured air kerma data are available, these should be used. If not, air kerma rates can be estimated from Figure 3-1 (ICRP 1982) if average technique factors and total filtration are known.

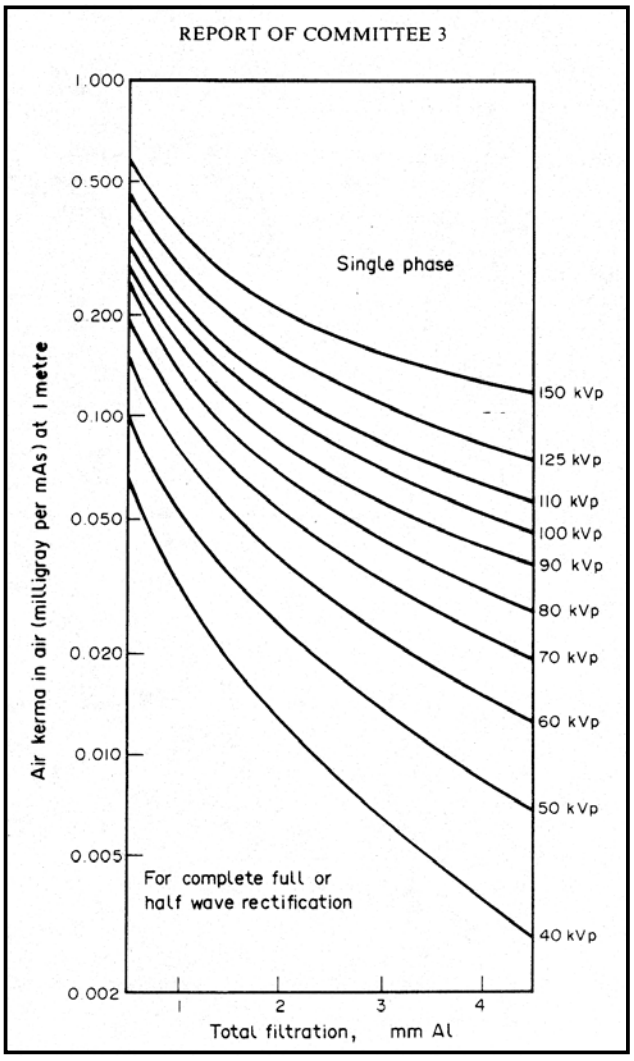

Figure 3-1. Kerma in air at 1 m from X-ray source as a function of total filtration for various values of tube potential (from ICRP 1982).

Figure 3-1 is for single-phase machines; results should be multiplied by 1.8 for three-phase machines. The machine present at RFP from June 11, 2001, until Plant closure is assumed to have been three-phase. Once the kerma rate is estimated, the air kerma at 100 cm is calculated by multiplying the estimated air kerma rate by the number of mAs used for each radiograph (ICRP 1982).

Next, the source-to-skin distance (SSD) is calculated by subtracting the AP or LAT thickness of the standard (reference) worker or person and distance between the worker and the film (default distance of 5 cm) from the SID. Air kerma at the SSD is then estimated using the following equation:

$$\textit{air kerma at SSD}\ (\text{mGy}) = (100/\text{SSD})^2 \times \textit{air kerma at 1 m}\ (\text{mGy}) \qquad (3\text{-}2)$$

Tables A.2 through A.9 of ICRP (1982) are then used to estimate organ dose directly. Dose to the skin was estimated by multiplying the air kerma at SSD by the appropriate factor from Table B-8 of National Council of Radiation Protection and Measurements Report 102 (NCRP 1989). The tables list organ doses in milligray normalized to an air kerma of 1 Gy in air at the skin, as a function of half-value layers (HVLs) in millimeters of aluminum. In addition, ICRP (1982, Appendix A) provides tables for estimating the HVL if it is not known. Table 3-4 lists all such values used in this TBD.

Table 3-4. ICRP dose conversion factors; absorbed dose (1 mGy) for organs at various Al HVL (1-Gy entrance air kerma in air without backscatter). Image size 35.6 by 43.2 cm (ORAUT 2005).

Organ	Chest PA (pre-1970)[a,b] at 2.5 mm Al HVL SID = 183 cm Entrance kerma = 0.2 cGy	Chest PA[a] (1970 to 1985) at 2.5 mm Al HVL SID=183 cm Entrance kerma = 0.1 cGy	Chest PA[a] (1985 to present) at 4 mm Al HVL SID = 183 cm Entrance kerma = 0.05 cGy (prior to 2001)	Lumbar spine[c] at 2 mm Al HVL AP	Lumbar spine[c] at 2 mm AL HVL LAT
Thyroid	174[d]	32	78	0.2	0.01
Eye/brain	32	32	78	0.2	0.01
Ovaries	N/A	1	5.2	N/A	N/A
Liver/gall bladder/spleen	451	451	674	62	10
Urinary bladder	N/A	1	5.2	N/A	N/A
Colon/rectum	N/A	1	5.2	N/A	N/A
Testes	N/A	0.01	0.01	N/A[e]	N/A
Lungs (male)	419	419	628	62	10
Lungs (female)	451	451	674	62	10
Thymus	451	451	674	62	10
Esophagus	451	451	674	62	10
Stomach	451	451	674	62	10
Bone surfaces	451	451	674	62	10
Remainder	451	451	674	62	10
Breast	49	49	116	18[f]	9.5[f]
Uterus (embryo)	N/A	1.3	5.2	N/A	N/A
Bone marrow (male)	92	92	178	24	15
Bone marrow (female)	86	86	172	24	15
Skin	N/A	N/A	N/A	1.32	1.32

N/A = as reported in ORAUT (2005).

a. Dose conversion factors from ICRP (1982, Tables A.2 through A.9), ORAUT (2005).
b. Assumes minimal collimation.
c. From ORAUT (2005).
d. Dose conversion factor for AP cervical spine, corrected for depth by 0.2.
e. Organ dose values for the testes, ovaries, and lumbar spine reflect actual measurement per Lincoln and Gupton (1958).
f. Dose conversion factors for lumbar spine examination not given in ICRP (1982). Values for the respective upper gastrointestinal examinations (i.e., AP and LAT) were used instead.

The ICRP tables used to estimate absorbed dose do not include all organs that have been identified in the Interactive RadioEpidemiological Program (IREP) computer program. For those organs included in the IREP but not specifically identified in the ICRP tables, the dose conversion coefficient

that is anatomically closest to the IREP-specified organs can be used 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 (ORAUT 2005). For abdominal organs (e.g., bladder, colon), the dose coefficient for ovaries should be used (ORAUT 2005). This approach should be either favorable to claimants or neutral. Table 3-5 provides analogs for IREP organs.

Table 3-5. Analogs for IREP organs not specified in ICRP (1982).[a]

Anatomical location	ICRP (1982) reference organ	IREP organ analogs	
Thoracic cavity	Lung	Thymus Esophagus Stomach	Bone surface Liver/gall bladder/spleen Remainder organs
Abdominal cavity	Ovaries	Urinary bladder	Colon/rectum
Head and neck	Thyroid	Eye/brain	

a. As presented in ORAUT (2005).

Dose estimates for PA chest X-rays and prehire AP and LAT lumbar spine X-rays are presented in Tables 3-6 and 3-7 for each organ listed in ICRP (1982). All dose estimates are default values as presented in ORAUT (2005) except those for June 11, 2001, to present, which are based on known machine settings (Dean 2003) and information such as HVL supplied by former medical workers (Lopez 2003).

PFG could have been used at RFP, but no information about protocol has been found. Lacking any further information on PFG at RFP (notes indicate only that a fluoroscope was removed in 1968 and workers recall a "portable x-ray machine" being used), default dose estimates have been used (ORAUT 2005). It is assumed, until further information is found, that the frequency of PFG was once per year from 1952 to 1968, and that it was used for the chest only [15]. As noted, a fluoroscope is not the same as photofluorography equipment (ORAUT 2005) but, considering the uncertainty of PFG use at RFP and input from former workers, PFG cannot be ruled out. The dose estimates should be used if a worker's file indicates a PFG examination.

3.5.2 Organ Dose Estimates for RFP Workers

Table 3-6 lists default organ dose estimates from PA chest X-rays for each period. Table 3-7 lists the default organ dose estimates for AP and LAT lumbar spine X-rays (note that the values have been halved to account for two views; ORAUT 2005). Table 3-8 lists default PFG exposure from chest examinations (ORAUT 2005).

At this time, there is insufficient information to calculate site-specific organ doses for RFP from chest X-rays before 2001, all lumbar spine X-rays, and all PFG examinations. The organ doses presented here will be revised if additional site-specific information is found that allows the calculation of organ doses.

3.6 UNCERTAINTIES

As stated in ORAUT (2005), *error* is defined as deviation from the correct, true, or conventionally accepted value of a quantity, and *uncertainty* is defined 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).

Table 3-6. Organ dose estimates for PA chest (mGy)

Period: June 11, 2001, to present [16]

Organ	Estimated dose[a] HVL = 4.0 mm AL Air kerma at skin = 0.134 mGy	
	mGy	rem
Thyroid	1.05E-02	1.05E-03
Eye/brain	1.05E-02	1.05E-03
Ovaries	6.99E-04	6.99E-05
Liver/gall bladder/ spleen	9.06E-02	9.06E-03
Urinary bladder	6.99E-04	6.99E-05
Colon/rectum	6.99E-04	6.99E-05
Testes	1.34E-06	1.34E-07
Lungs (male)	8.44E-02	8.44E-03
Lungs (female)	9.06E-02	9.06E-03
Thymus	9.06E-02	9.06E-03
Esophagus	9.06E-02	9.06E-03
Stomach	9.06E-02	9.06E-03
Bone surfaces	9.06E-02	9.06E-03
Remainder	9.06E-02	9.06E-03
Female breast	1.56E-02	1.56E-03
Uterus	6.99E-04	6.99E-05
Bone marrow (male)	2.39E-02	2.39E-03
Bone marrow (female)	2.31E-02	2.31E-03
Skin	1.91E-01	1.91E-02

Period: 1985 to June 4, 2001

Organ	Estimated dose[b] HVL = 4.0 mm Al; Entrance kerma = 0.05 cGy	
	mGy	rem
Thyroid	3.90E-02	3.90E-03
Eye/brain	3.90E-02	3.90E-03
Ovaries	2.60E-03	2.60E-04
Liver/gall bladder/ spleen	3.37E-01	3.37E-02
Urinary bladder	2.60E-03	2.60E-04
Colon/rectum	2.60E-03	2.60E-04
Testes	5.00E-06	5.00E-07
Lungs (male)	3.14E-01	3.14E-02
Lungs (female)	3.37E-01	3.37E-02
Thymus	3.37E-01	3.37E-02
Esophagus	3.37E-01	3.37E-02
Stomach	3.37E-01	3.37E-02
Bone surfaces	3.37E-01	3.37E-02
Remainder	3.37E-01	3.37E-02
Female breast	5.80E-02	5.80E-03
Uterus	2.60E-03	2.60E-04
Bone marrow (male)	8.90E-02	8.90E-03
Bone marrow (female)	8.60E-02	8.60E-03
Skin	7.00E-01	7.00E-02

Table 3-6 (Continued). Organ dose estimates for PA chest.

Period: post 1970 to 1985

Organ	Estimated dose[b] HVL = 2.5 mmAl; Entrance kerma = 0.10 cGy	
	mGy	rem
Thyroid	3.20E-02	3.20E-03
Eye/brain	3.20E-02	3.20E-03
Ovaries	1.00E-03	1.0E-04
Liver/gall bladder/ spleen	4.51E-01	4.51E-02
Urinary bladder	1.00E-03	1.00E-04
Colon/rectum	1.00E-03	1.00E-04
Testes	1.00E-05	1.00E-06
Lungs (male)	4.19E-01	4.19E-02
Lungs (female)	4.51E-01	4.51E-02
Thymus	4.51E-01	4.51E-02
Esophagus	4.51E-01	4.51E-02
Stomach	4.51E-01	4.51E-02
Bone surfaces	4.51E-01	4.51E-02
Remainder	4.51E-01	4.51E-02
Female breast	4.90E-02	4.90E-03
Uterus	1.30E-03	1.30E-04
Bone marrow (male)	9.20E-02	9.20E-03
Bone marrow (female)	8.60E-02	8.60E-03
Skin	1.35E+00	1.35E-01

Period: pre-1970

Organ	Estimated dose[b] HVL = 2.5 mmAl; Entrance kerma = 0.20 cGy	
	mGy	rem
Thyroid	3.48E-01	3.48E-02
Eye/brain	6.40E-02	6.40E-03
Ovaries	2.50E-01[c]	2.50E-02[c]
Liver/gall bladder/spleen	9.02E-01	9.02E-02
Urinary bladder	2.50E-01[c]	2.50E-02[c]
Colon/rectum	2.50E-01[c]	2.50E-02[c]
Testes	5.00E-02[c]	5.00E-03[c]
Lungs (male)	8.38E-01	8.38E-02
Lungs (female)	9.02E-01	9.02E-02
Thymus	9.02E-01	9.02E-02
Esophagus	9.02E-01	9.02E-02
Stomach	9.02E-01	9.02E-02
Bone surfaces	9.02E-01	9.02E-02
Remainder	9.02E-01	9.02E-02
Female breast	9.80E-02	9.80E-03
Uterus	2.50E-01[c]	2.50E-02[c]
Bone marrow (male)	1.84E-01	1.84E-02
Bone marrow (female)	1.72E-01	1.72E-02
Skin	2.70E+00	2.70E-01

a. HVL determined from former medical workers (Lopez 2003); machine settings from a memorandum to file (Dean 2003).
b. As presented in ORAUT (2005)
c. Modified from Webster and Merrill (1957) as presented in ORAUT (2005).

Table 3-7. Organ dose estimates for AP and LAT lumbar spine (1952–1974).

Organ	AP lumbar spine[a] ESE = 2 rem (rem)	LAT lumbar spine ESE = 5 rem (rem)
Thyroid	4.00E-04	5.00E-05
Eye/brain	4.00E-04	5.00E-05
Ovaries[b]	5.60E-01	7.60E-01
Urinary bladder	5.60E-01	7.60E-01
Colon/rectum	5.60E-01	7.60E-01
Testes[b]	2.70E-02	5.60E-02
Lung	1.24E-01	5.00E-02
Liver/gall bladder/spleen	1.24E-01	5.00E-02
Thymus	1.24E-01	5.00E-02
Esophagus	1.24E-01	5.00E-02
Stomach	1.24E-01	5.00E-02
Bone surfaces	1.24E-01	5.00E-02
Remainder	1.24E-01	5.00E-02
Female breast	3.60E-02	4.75E-02
Uterus	4.34E-01	1.00E-01
Bone marrow	4.80E-02	7.50E-02
Skin[c]	2.64E+00	6.60E+00

a. As presented in ORAUT (2005); value is halved from that in ORAUT (2005) because file review indicated that only AP and LAT views were taken.
b. Organ dose values for the testes and ovaries for lumbar spine reflect actual measurement reported in Lincoln and Gupton (1958).
c. Skin dose values include backscatter factor of 1.32 from NCRP (1989, Table B.8).

Table 3-8. Organ dose estimates for photofluorography, 1952 to 1968 (as presented in ORAUT 2005). Entrance kerma = 3 cGy; HVL = 2.5 mm Al; all estimates are for uncollimated beams.

Organ	View	Dose conversion factor (mGy per Gy air kerma)[a] HVL 2.5 mm Al uncollimated	Organ dose (rem) uncollimated
Thyroid	PA	174[b]	5.22E-01
Eye/brain	PA	32	9.60E-02
Ovaries	PA	N/A	2.50E-02[c]
Liver/gall bladder	PA	451	1.35E+00
Urinary bladder	PA	N/A	2.50E-02[c]
Colon/rectum	PA	N/A	2.50E-02[c]
Testes	PA	N/A	5.00E-03[c]
Lungs (male)	PA	419	1.26E+00
Lungs (female)	PA	451	1.35E+00
Thymus	PA	451	1.35E+00
Esophagus	PA	451	1.35E+00
Stomach	PA	451	1.35E+00
Bone surfaces	PA	451	1.35E+00
Remainder	PA	451	1.35E+00
Breast	PA	49	1.47E-01
Uterus	PA	N/A	2.50E-02[c]
Bone marrow (male)	PA	92	2.76E-01
Bone marrow (female)	PA	86	2.58E-01
Skin[c]	PA		4.05E+00

a. Dose conversion factors from, ICRP (1982, Tables A.2 through A.9).
b. Dose conversion factor for AP cervical spine, corrected for depth by 0.2 (ORAUT 2005).
c. Modified from Webster and Merrill (1957), as reported in ORAUT (2005).

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 SSD. Film speed, use of screens, or use of grids would not affect the beam output intensity. The lack of records for these measurements for most years at RFP introduces a large uncertainty into the dose estimates that cannot be readily quantified, although there is no apparent reason to believe that practices at RFP were different from those at other facilities or from recommended standards of the medical community at the time [17]. Therefore, use of default estimates and reliance on information from other DOE sites when site-specific information was also unavailable is likely to closely approximate X-ray performance at RFP. The following estimates of uncertainty associated with X-ray exposure are from ORAUT (2005), which was relied upon for default information. Further, these same factors affect dose estimates of PFG X-rays; proxy default information for PFG was taken from ORAUT (2005) in the absence of useful records at RFP.

ORAUT (2005) reports that X-ray doses are largely derived from actual measurements of X-ray machine output with R-meters or similar ionization chamber devices. Reportedly, these typically had an uncertainty of ±2% for photon energies below 400 keV, if properly calibrated and used. Although machinery that is more current might have a smaller uncertainty, ±2% should be used 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, which results in an uncertainty of approximately 9% in relation to beam intensity for voltages in the 110- to- 120-kVp range (ORAUT 2005).

Variations in tube current are normal and generally small. As tube current drops, beam intensity also falls in direct proportion to the tube current. Large decreases in beam output would be readily detected 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. However, there is no evidence that such a procedure was ever needed or applied at RFP. Consistent with ORAUT (2005), the variation in tube current is assumed to be approximately ±2%.

Exposure time can also significantly affect the dose received from radiography (exposure times are a fraction of a 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, uncertainty in beam output due to timers is assumed to be ±25% (ORAUT 2005). Therefore, it is recommended that ±25% be applied for RFP estimates, particularly since site-specific exposure time was available only for the present machine.

Last, SSD can contribute to variability because the entrance skin exposure is determined by this distance. Variations result from accuracy of positioning as well as worker size (thickness). As expressed in ORAUT (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 RFP is the number of X-rays taken. As noted above, medical files reviewed for this TBD showed that the files did not always document X-rays taken, at least before the mid-1970s. Further, the frequency of PFG is completely unknown. It is recommended that, as a conservative approach, an annual chest X-ray should be assumed for all energy employees of RFP. It should also be assumed that AP and LAT lumbar spine X-rays were taken at the start of employment for all individuals employed from 1952 to 1974. If a record of PFG

use is found in an individual's claim file, an annual PFG X-ray of the chest should be assumed from 1952 to 1968 [18].

Consistent with ORAUT (2005), the statistical root mean square was calculated to estimate total uncertainty (ORAUT 2005). 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 is larger than the default NIOSH guidance standard deviation recommendation of 20% (NIOSH 2002).

3.7 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 here again in the Attributions section of the document, with information provided to identify the source and justification for each associated item. Conventional references are provided in the next section of this document, linking data, quotations, and other information to documents available for review on the ORAU Team servers.

[1] Lopez, Theresa. MFG. Senior Toxicologist. July 2006.
In the absence of data or protocols, assumptions that needed to be made were favorable to claimants.

[2] Furman, J. Oak Ridge Institute for Science and Education (ORISE). Former Medical Director, Rocky Flats Plant. July 2003.
Based on work history at the site and available protocols. Documented July 18, 2003.

[3] Furman, J. ORISE. Former Medical Director, Rocky Flats Plant. July 2003.
Based on review of medical files at RFP. Documented July 18, 2003.

[4] Furman, J. ORISE. Former Medical Director, Rocky Flats Plant. July 2003.
Based on review of medical files at RFP. Documented July 18, 2003.

[5] Furman, J. ORISE. Former Medical Director, Rocky Flats Plant. July 2003.
Based on review of medical files at RFP. Documented July 18, 2003.

[6] Lopez, Theresa. MFG. Senior Toxicologist. July 2006.
Many other DOE sites are known to have conducted termination X-rays. No protocol or record of termination X-rays as a standard practice has been found for RFP. A review of medical files did not indicate that the practice was common, if it occurred at all. However, former nonmedical employees assert that it did occur. Because this was a common practice at other DOE sites, it has been assumed to have occurred at RFP up to the date that a protocol stating otherwise was published. This assumption is favorable to claimants.

[7] Furman, J. ORISE. Former Medical Director, Rocky Flats Plant. July 2003.
Based on review of medical files at RFP and interviews with medical personnel. Documented July 18, 2003.

[8] Lopez, Theresa. MFG. Senior Toxicologist. July 2006.
In the absence of a protocol, it was assumed that all workers received these X-rays, even though they were more likely to have been related to job classification. This assumption is favorable to claimants.

[9] Furman, J. ORISE. Former Medical Director, Rocky Flats Plant. July 2003.
Based on personal history of working at the site and medical file review. Documented July 18, 2003.

[10] Furman, J. ORISE. Former Medical Director, Rocky Flats Plant. July 2003.
Based on review of medical files. Documented July 18, 2003.

[11] Lopez, Theresa. MFG. Senior Toxicologist. July 2006.
An annual single-view chest X-ray is likely an overestimate of actual practice because a review of medical files found that chest X-rays rarely occurred on an annual basis, probably due to scheduling and machine availability. However, this assumption is favorable to claimants because it encompasses more X-rays than were probably taken.

[12] Furman, J. ORISE. Former Medical Director, Rocky Flats Plant. July 2003.
Documented July 18, 2003. Also documented by Robert Meyer, August 13, 2003.

[13] Furman, J. ORISE. Former Medical Director, Rocky Flats Plant. July 2003.
Based on review of medical files and discussions. Documented July 18, 2003.

[14] Furman, J. ORISE. Former Medical Director, Rocky Flats Plant. July 2003.
Based on medical personnel interviews and review of medical files. Documented July 18, 2003.

[15] Lopez, Theresa. MFG. Senior Toxicologist. July 2006.
No PFG records or protocols have been found. PFG has been assumed to have possibly occurred because former workers recall the use of a “portable x-ray machine.” However, former medical employees do not recall performing PFG.

[16] Lopez, Theresa. MFG. Senior Toxicologist. July 2006.
Calculated from information given to J. Furman by the Occupational Medicine Group at RFP. Documented July 18, 2003.

[17] Furman, J. ORISE. Former Medical Director, Rocky Flats Plant. July 2003.
Based on personal work history at the site.

[18] Lopez, Theresa. MFG. Senior Toxicologist. July 2006.
See Attribution and Annotation [15]. This assumption is favorable to claimants.

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Webster, E. W., and O. E. Merrill, 1957, "Measurements of Gonadal Dose in Radiographic Examinations," *New England Journal of Medicine*, volume 257, pp. 811-819.

GLOSSARY

curie (Ci)
A special unit of activity. One curie equals exactly 3.7×10^{10} nuclear transitions per second.

exposure
Expressed in roentgens (R): the ionization produced by photon (gamma and X-ray) radiation in air.

extremities
Elbow through fingers; knee through toes.

gamma rays
Ionizing electromagnetic radiation (photons) originating from atomic nuclei.

gray (Gy)
The International System unit of absorbed dose.

lumbosacral spine
The five lumbar and five sacral vertebrae of the spine.

neutron
Neutral nuclear particle; mass nearly the same as the proton.

personal dose equivalent $H_p(d)$
Represents the dose equivalent in soft tissue below a specified point on the body at an appropriate depth *d*. The depths selected for personnel dosimetry are 0.07 mm and 10 mm, respectively, for the skin and body. These are noted as $H_p(0.07)$ and $H_p(10)$, respectively.

photon (ionizing)
X- or gamma radiation.

photon - X-ray
Electromagnetic radiation of energies between 10 keV and 100 keV whose source can be an X-ray machine or radioisotope.

radiation
Alpha, beta, neutron, X-, or gamma radiation.

radioactivity
The spontaneous emission of radiation from unstable nuclei.

rem
A unit of dose equivalent, equal to the product of the number of rads absorbed and the quality factor.

roentgen (R)
A unit of exposure to gamma (or X-) radiation. It is defined as the quantity of gamma (or X) rays that will produce a total charge of 2.58×10^{-4} coulomb in 1 kg of dry air. An exposure of 1 R is approximately equivalent to an absorbed dose of 1 rad in soft tissue for higher (~>100 keV) energy photons.

shielding

Any material or obstruction that diminishes or attenuates radiation and thus can protect personnel or materials from radiation.

sievert (Sv)

The SI unit for dose equivalent. (1 Sv = 100 rem.)

skin dose

Absorbed dose at a tissue depth of 7 mg/cm^2.

X-ray

(1) Radiograph. (2) Ionizing electromagnetic radiation produced outside the nucleus.