ORAU Team **NIOSH Dose Reconstruction Project** Technical Basis Document for the Rocky Flats Plant – Occupational Medical Dose	Document Number: ORAUT-TKBS-0011-3 Effective Date: 02/09/2004 Revision No.: 00 Controlled Copy No.: _____ Page 1 of 27
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RECORD OF ISSUE/REVISIONS

ISSUE AUTHORIZATION DATE	EFFECTIVE DATE	REV. NO.	DESCRIPTION
Draft	10/31/2003	00-A	New Technical Basis Document for the Rocky Flats Plant – Occupational Medical Dose. Initiated by Robert Meyer.
Draft	11/26/2003	00-B	Revised in accordance with comments received 10/14/03 and 11/14/03 (all comments received to date). Initiated by Robert Meyer.
Draft	12/26/2003	00-C	Photofluorography assumptions modified per email messages this week. Initiated by Robert Meyer.
Draft	01/05/2004	00-D	Modified per ORAU (Elyse Thomas) comments received 12/30/03. Initiated by Robert Meyer.
Draft	02/02/2004	00-E	Incorporates NIOSH review comments. Initiated by Robert Meyer.
Draft	02/06/2004	00-F	Modified per discussions with Mr. Tim Taulbee. Initiated by Robert Meyer.
02/09/2004	02/09/2004	00	First approved issue. Initiated by Robert Meyer.

ACRONYMS AND ABBREVIATIONS

α	alpha particle
AEC	(U.S.) Atomic Energy Commission
AECL	Administrative Exposure Control Level
AED	Aerodynamic Equivalent Diameter
AEDE	Annual Effective Dose Equivalent
AP	anterior-posterior
AWE	Atomic Weapons Employer
β	beta particle
CATI	Computer Assisted Telephone Interview
CDPHE/CDH	Colorado Department of Public Health and Environment (Previously Colorado Department of Health)
CEDE	Committed Effective Dose Equivalent (replaced the AEDE in 1992)
CFR	Code of Federal Regulations
c/m	counts per minute
DAC	Derived Air Concentration
DE	Dose Equivalent
DL	Detection Limit
DOE	U.S. Department of Energy
DOELAP	DOE Laboratory Accreditation Program
DOL	Department of Labor
DU	Depleted Uranium
EEOICPA	Energy Employees Occupational Illness Compensation Program Act
EPA	Environmental Protection Agency (U.S.)
ERDA	Energy Research & Development Administration
ETF	Effluent Treatment Facility

γ	gamma ray
Gy	gray
HEU	Highly Enriched Uranium
HHS	Department of Health and Human Services
Hp(10)	Personal Dose Equivalent
HPRED	Health Protection Radiation Exposure Database
HPAREH	Health Protection Annual Radiation Exposure History Database
HVL	Half-value layers
IARC	International Agency for Research on Cancer
ICRP	International Commission on Radiological Protection
IMBA	Integrated Modules for Bioassay Analysis
IREP	Interactive RadioEpidemiological Program
kerma	kinetic energy released per unit mass
keV	kilo electron Volt
kV	kilovolt
kVp	kilovolt-peak
LANL	Los Alamos National Laboratory
LAT	lateral
LLD	Lower Limit of Detection
mA	milliamp-second
MDA	Minimum Detectable Activity
MDL	Minimum Detection Limit
MED	Manhattan Engineering District
MEPAS	Multimedia Environmental Pollutant Assessment System
mGy	milligray
mmAl	millimeters of aluminum

NCRP	National Council on Radiation Protection and Measurements
NIOSH	National Institute for Occupational Safety and Health
NOCTS	NIOSH Occupational Claims Tracking System
NTA	Nuclear Track Emulsion
OCAS	Office of Compensation Analysis and Support
ORAU	Oak Ridge Associated Universities
ORNL	Oak Ridge National Laboratory
PA	posterior-anterior (medical x-ray)
PAS	Personal Air Sampler
PIC	Pocket Ionization Chamber (i.e., “Pencil” dosimeter)
Pu	Plutonium
R	Roentgen
RAS	Regional Air Sampler
RBE	Relative Biological Effectiveness
RC & HP	Radiological Control and Health Physics Department
rem	Roentgen equivalent man
rep	Roentgen equivalent physical
RFP	Rocky Flats Plant
RRF	Resin Regeneration Facility
RTF	Replacement Tritium Facility
RU	Recycled Uranium
s	second
SEC	Special Exposure Cohort
SID	source to image distance
SRS	Savannah River Site

SSD	source to skin distance
SWDF	Solid Waste Disposal Facility
TBD	Technical Basis Document
TEPC	Tissue Equivalent Proportional Counter
TLD	Thermoluminescent Dosimeter
TLND	Thermoluminescent Neutron Dosimeter
TPO	Technical Procedures Office
TRU	Transuranic
U.S.C.	United States Code
WCF	Waste Certification Facility

3.0 OCCUPATIONAL MEDICAL DOSE

As part of the requirements for employment at the Rocky Flats Nuclear Weapons Plant (RFP), entrance, exit, and periodic physical examinations were performed on all employees. These physical examinations could include radiographic examinations of the lungs and, for some employees, the lumbar spine. Because these examinations were required for employment, the Office of Compensation Analysis and Support (OCAS) *External Dose Reconstruction Implementation Guidelines* (OCAS 2002) and 42 CFR Part 82, the implementing regulation for the Energy Employees Occupational Illness Compensation Program Act of 2000 (Public Law 106-398) consider the X-ray doses to be part of the occupational radiation exposure. Only medical exposures that were required as a condition of employment are included; diagnostic and therapeutic procedures not required for employment are excluded.

The following sections describe the methodology used to estimate absorbed dose from X-ray exposure for RFP workers. In the absence of available data, assumptions are generally conservative (claimant-favorable). Section 3.1 provides introductory text. Section 3.2 describes X-ray examination frequency at Rocky Flats. Section 3.3 provides information on equipment and techniques used at Rocky Flats, 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.

3.1 Introduction

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 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 (R). The current international system of units expresses this quantity in *air kerma* (kerma is an acronym for 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 OCAS guidelines (OCAS 2002) is:

$$D_{om} = \Sigma nDi \qquad (3.1\text{–}1)$$

where

D_{om} = occupational medical dose
n = number of exams in a calendar year
Di = dose from the X-ray procedure

The OCAS guidelines direct 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 (a claimant-favorable assumption). The guidance states that the uncertainty distribution about each X-ray procedure is assumed to follow a normal distribution, with D_{om} being the mean dose.

3.2 Examination Frequency

The frequency of X-ray examinations varied significantly for RFP workers (Table 3.2-1). A protocol for frequency of a single PA (posterior-anterior) 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 years for respirator wearers, and annually for beryllium and asbestos workers over age 45 and with a 10-year history of asbestos exposure. 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.) Inspection of medical records has not revealed any more specific designation of workers who would receive nearly annual chest X-rays. Based on the records reviewed during preparation of this document, no worker received such exams more often than annually.

Between 1952 and 1974, all workers received spinal X-rays during their initial employment 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.

Without a review of the specific claimant'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-1970's. A claimant-favorable approach to the estimation of the X-rays taken would therefore assume lumbosacral spine X-rays were taken if the claimant 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 "retakes" necessary because of poor quality of the initial x-ray.

3.3 Equipment and Techniques

Although RFP radiological practices are assumed to have followed standards of medical practice to minimize dose to the patient, the type of equipment, technique factors, and machine calibrations are not fully known for years before 2001. Members of the Rocky Flats TBD team interviewed Medical and Records group staff and Colorado Department of Public Health and Environment staff, and determined that X-ray machine records for equipment in use before 2001 are not readily available. However, some information has been located regarding equipment type and ratings; this data has been used provided in conjunction with default data where needed to provide claimant-favorable estimates of potential exposure. 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.

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 time periods (ORAU 2003a). 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 (claimant-favorable). The default dose estimates are from the Complex-Wide X-ray Technical Information Bulletin (TIB) (ORAU 2003a) for chest X-rays, and from information presented in Lincoln and Gupton (1958) for lumbar spine X-rays.

Photofluorography may have been performed at RFP. While no particular records or protocol have been found, a note indicating that a fluoroscope was removed from the plant in 1968 indicates that photofluorography could have been performed. As no further site-specific information has been found

to date, default estimates of exposure from the Complex-Wide TIB (ORAU 2003a) have been used in this report.

Efforts will continue to locate all related information for RFP. However, until more accurate records are located, these assumptions provide the most claimant-favorable estimates.

Tables 3.3-1 and 3.3-2 summarize known information regarding equipment and techniques.

3.4 Organ Dose Estimates

Organ dose estimates are provided in this section. Section 3.4.1 describes the methodology used to estimate these doses; Section 3.4.2 discusses the results.

3.4.1 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 (cm)
2. Total Filtration (millimeters of aluminum, mm Al)
3. Estimate of patient thickness (AP and LAT)
4. Machine settings (mA, 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 3.4.1-1.

Figure 3.4.1-1 is for single-phase machines; results should be multiplied by 1.8 for three-phase machines. All X-ray machines at RFP were assumed to be 3-phase, as a conservative measure. 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 mA used for each radiograph.

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

$$\text{air kerma at SSD (mGy)} = (100/\text{SSD})^2 \times \text{air kerma at 1 meter (mGy)} \qquad (3.4.1\text{–}1)$$

Tables A-2 through A-9 of ICRP 34 (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 the National Council of Radiation Protection and Measurements Report 102 (NCRP 1989). The tables list organ doses in mGy normalized to an air kerma of 1 Gy in air at the skin, as a function of half-value layers (HVL) in millimeters of aluminum. In addition, ICRP (1982) Appendix A provides tables for estimating the HVL if it is not known. Table 3.4.1-1 lists all such values used in this report.

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 may 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. For abdominal organs (bladder, colon), the dose coefficient for

ovaries should be used. This approach should be either claimant-favorable or neutral. Table 3.4.1-2 provides analogs for IREP organs.

To determine doses from lumbar spine x-rays, data from Lincoln and Gupton (1958) was used to create probability distributions for each organ listed in ICRP 34 (1982). The paper listed doses to skin, testes, and ovaries from several different x-ray examination procedures at eight Oak Ridge National Laboratory (ORNL) facilities. Doses were measured using a manikin, and both filtration and collimation varied by facility, reflecting typical procedures employed at each facility at the time.

To create the probability distributions, the entrance skin exposures (ESEs) listed in the Lincoln and Gupton paper (1958) for AP and LAT lumbar spine x-rays was entered into Crystal Ball® software (Decisioneering Inc. 2000) to predict a distribution of exposure for each view. Then, corrected for units, the ESEs were multiplied by a distribution of dose conversion factors for AP and LAT lumbar spine x-rays for each organ listed in ICRP 34 (1982). Dose conversion factors corresponding to total filtrations of 1.5 mmAl to 3.0 mmAl were used in the calculations. This assumption is necessary because filtration values presented in the Lincoln and Gupton paper (1958) ranged from 0 mmAl to 3.0 mmAl; it is unknown whether these values represented added or total filtration. Further, the ICRP 34 tables present dose conversion factors for total filtration only, with a minimum of 1.5 mmAl and maximum of 4.0 mmAl. It was assumed that 3.0 mmAl was the maximum filtration for this time period and view. The dose conversion factors were assumed to have uniform distribution (equal probability of occurrence).

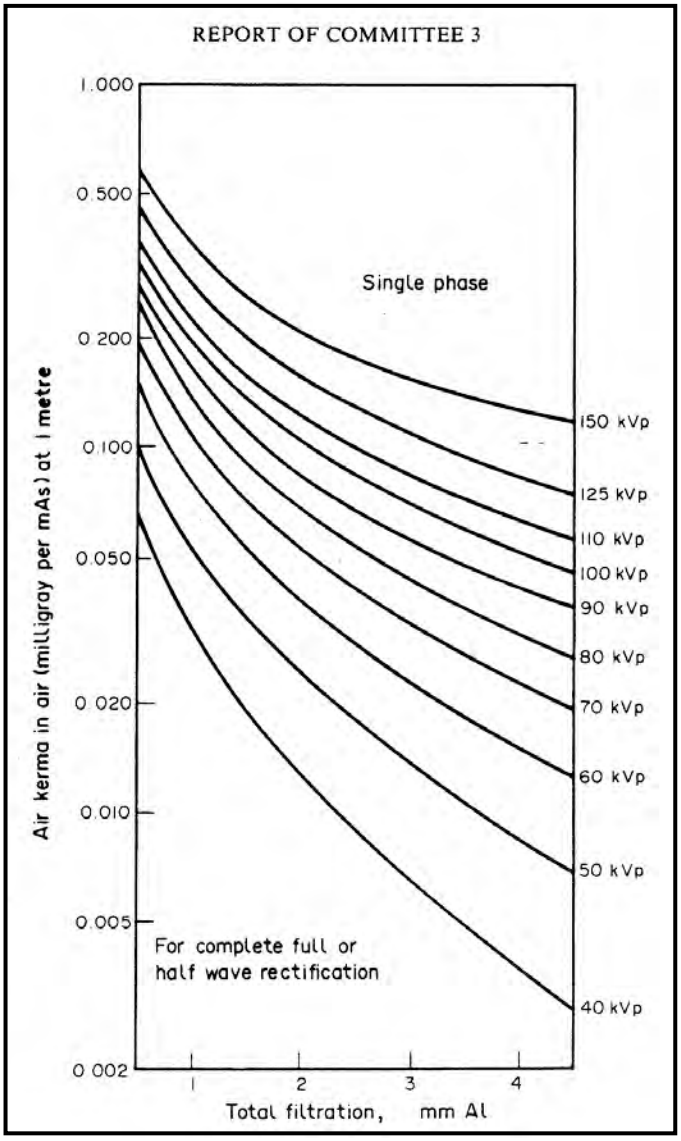

Figure 3.4.1-1. Kerma in air at 1 meter from X-ray source as a function of total filtration for various values of tube potential (from ICRP 1982).

The resulting forecasts of dose for each organ were used to estimate average dose for AP and LAT lumbar spine x-rays, with one exception. The dose to the testes predicted by the model did not correspond to the measured doses; this is due to restrictive collimation assumed in the dose conversion factors. Lack of collimation resulted in higher measured dose in the Lincoln and Gupton paper (1958). The measured dose to the testes, therefore, was used in these dose estimates (the geometric mean after removal of one extreme upper-bound value in both the AP and LAT estimates) (Lopez 2004). For each organ, the geometric mean of the forecasted estimates (or measured dose, for the testes) was used as the dose. Results are listed in Table 3-4.2-2 and supporting material is provided as Attachment A to this section.

Photofluorography could have been used at RFP, but no information regarding protocol has been located. Lacking any further information on photofluorograpy at RFP (notes indicate only that a fluoroscope was removed in 1968) default dose estimates from the Complex-Wide TIB have been used. It is assumed, until further information is located, that the frequency of photofluorography was once per year from 1953 to 1968, and that it was used for the chest only.

3.4.2 Organ Dose Estimates for RFP Workers

Table 3.4.2-1 lists default and calculated organ dose estimates from PA chest X-rays for each period. Table 3.4.2-2 lists the calculated organ dose estimates for AP and LAT lumbar spine X-rays (derived from information in Lincoln and Gupton 1958). Table 3.4.2-3 presents default photofluorography exposure from chest examinations, as reported in the Complex-Wide TIB (ORAU 2003a).

Note that some estimates for exposure from PA chest X-rays from 1953 to 2001 are based on information taken from the Complex-Wide TIB (ORAU 2003a). Specifically, default estimates for time periods prior to 2001 have been used. For lumbar spine dose estimates, measured and estimated doses from information in Lincoln and Gupton (1958) have been used, as described above, as site-specific information is currently unavailable.

In addition, estimated doses associated with photofluorography have been taken from the Complex-Wide TIB (ORAU 2003a), as no information is available at this time for RFP. As noted above, photofluorography may have been used at RFP prior to 1968.

3.5 Uncertainties

As stated in the Complex-Wide TIB and Savannah River Site TBD (ORAU 2003a,b), 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).

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 the use of grids would not affect the beam output intensity. The lack of historical records for these measurements for most years at Rocky Flats introduces a large uncertainty into the dose estimates that cannot be readily quantified, although there is no apparent reason to believe that practices at Rocky Flats were different from those at other facilities or from recommended standards of the medical community at the time. Therefore, use of default estimates and reliance on information from other DOE sites when site-specific information was unavailable is likely to closely approximate X-ray performance at RFP. The following estimates of uncertainty associated with X-ray exposure are from ORAU 2003a, which was relied upon for default information. Further, these same factors affect dose estimates of photofluorographic X-rays; proxy default information for photofluorography was taken from Complex-Wide (ORAU 2003a) in the absence of useful records at RFP.

The Complex-Wide TIB (ORAU 2003a) 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 $\pm$2% for photon energies below 400 keV, if properly

calibrated and used. Although machinery that is more current may 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, 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 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. The Complex-Wide TIB estimates the variation in tube current to be approximately ±2% (ORAU 2003a), while the Savannah River Site TBD listed a variation of ±5% for this parameter (ORAU 2003b). To be conservative, ±5% is recommended for RFP.

Exposure time may also 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, uncertainty in beam output due to timers is assumed to be ±25% in both the Complex-Wide TIB and Savannah River TBD documents (ORAU 2003a,b). 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 may contribute to variability, because the entrance skin exposure is determined by this distance. Variations result from accuracy of positioning as well as patient size (thickness). As expressed in the Complex-Wide TIB and Savannah River TBD documents, this is generally thought to vary by no more than a few centimeters, with an upper limit of 7.5 cm (±10%) (ORAU 2003a,b).

A potentially large source of uncertainty for RFP is the number of X-rays taken. As noted previously, 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 photofluorography is completely unknown. It is recommended that, as a conservative approach, an annual chest X-ray should be assumed for all claimants. 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. Unless otherwise indicated in an employee's medical record, an annual photofluorography x-ray of the chest should be assumed from 1953 to 1968.

Consistent with the Complex-Wide TIB and Savannah River Site TBD, the statistical root mean square was calculated to estimate total uncertainty (ORAU 2003a,b). 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 OCAS guidance standard deviation recommendation of 20% (OCAS 2002). Therefore, all final estimates were multiplied by 1.3 to account for uncertainty, conservatively assuming that all variables acted to increase dose (Tables 3.5-1. 3.5-2, and 3.5-3).

Table 3.2-1. Known X-ray examination frequencies.

Period	Frequency	View	Comment
1986-present	Annually	Chest (PA)	Beryllium and asbestos workers over age 45 years with 10 year work history exposure to asbestos
	Every 5th year	Chest (PA)	Respirator wearers
	None	Chest (PA)	Office personnel
1952-1985	Annual	Chest (PA)	Production workers
1952-1974	Once	Lumbar (AP and LAT)	All workers

Table 3.3-1. Description of X-ray equipment used at RFP and proxy information.

Classification	Period	Equipment	Source
Type I	June 11, 2001-present	Hologic/BXT202W	Furman 2003b; Dean, 2003
Type II	May 29, 1987 – March 6, 2001	Eureka XMA tube; Generator unknown	Furman 2003c; Dean, 2003
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 3.3-2. Equipment settings and ratings.

Machine	Period	View	Current (mA)	Voltage (kVp)	Exposure time (s)
Type 1[a]	6/11/2001-present	Chest PA	300	110	1/130
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
		Lumbar AP[c]	200	140	Unknown
		Lumbar LAT[c]	200	140	Unknown

a. Typical setting varies from 0.8 mA for an average-sized person to 2.3 mA for a very large person; 2.3 mA was used to be conservative.
b. Maximum machine ratings; data not used to calculate doses, but is presented for informational purposes.
c. Performed only from 1952 through 1974; settings are maximum machine ratings.

Table 3.4.1-1. 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 cm x 43.2 cm.

Organ	Chest PA (pre-1970) [a,b] at 2.5 mm Al HVL SID = 183 cm Entrance Kerma = 0.20 cGY	Chest PA [a] (1970 to 1985) at 2.5 mm Al HVL SID = 183 cm Entrance Kerma = 0.10 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 [d] range for 1.5 to 3.0 mm Al HVL AP	Lumbar spine [d] Range for 1.5 to 3.0 mm Al HVL LAT
Thyroid	174 (c)	32	78	0.06-0.6	0.01-0.01
Eye/Brain	32	32	78	0.06-0.6	0.01-0.01
Ovaries	N/A	1	5.2	105-274	17-67
Liver/Gall Bladder/Spleen	451	451	674	45-95	0.2-1.2
Urinary Bladder	N/A	1	5.2	105-274	17-67
Colon/Rectum	N/A	1	5.2	105-274	17-67
Testes	N/A	0.01	0.01	----	----
Lungs (male)	419	419	628	45-95	6-17
Lungs (female)	451	451	674	45-95	6-17
Thymus	451	451	674	45-95	6-17
Esophagus	451	451	674	45-95	6-17
Stomach	451	451	674	45-95	6-17
Bone Surfaces	451	451	674	45-95	6-17
Remainder	451	451	674	45-95	6-17
Breast	49	49	116	NC	NC
Uterus (embryo)	N/A	1.3	5.2	147-355	11-45
Bone marrow (male)	92	92	178	15-53	9.4-31
Bone marrow (female)	86	86	172	15-53	9.4-31
Skin	N/A	N/A	N/A	----	----

N/A = as reported in ORAU 2003a

NC = Not computed, but small in comparison to other organs

(a) Dose Conversion Factors from Tables A.2 through A.9, ICRP 1982 (ORAU 2003a); --- indicates not used; measured dose used instead of estimate

(b) Assumes minimal collimation

(c) Dose Conversion Factor for AP c-spine, corrected for depth by 0.2

(d) From ORAU 2003c.

Table 3.4.1-2. Analogs for IREP organs not specified in ICRP (1982).

Anatomical location	ICRP #34 reference organ	IREP organ analogues	
Thoracic cavity	Lung	Thymus Esophagus Stomach Bone surface	Liver/gall bladder/spleen Remainder organs
Abdominal cavity	Ovaries	Uterus Urinary bladder	Colon/rectum
Head and neck	Thyroid	Eye/brain	

Table 3.4.2-1. Organ dose estimates for PA chest (mGy).

Time period: June 11, 2001 to present

Organ	Estimated dose HVL = 4.0 mmAL 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	6.99E-04	6.99E-05
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

Time Period: 1985 to June 4, 2001

Organ	Estimated dose (a) HVL = 4.0 mmAl; Entrance Kerma = 0.05 cGy	
	mGy	rem
Thyroid	3.9E-02	3.9E-03
Eye/Brain	3.9E-02	3.9E-03
Ovaries	2.6E-03	2.6E-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	2.6E-03	2.6E-04
Bone marrow (male)	8.90E-02	8.90E-03
Bone marrow (female)	8.6E-02	8.6E-03
Skin	7.00E-01	7.00E-02

Table 3.4.2-1. Organ dose estimates for PA chest (continued)

Time Period: post 1970 to 1985

Organ	Estimated dose (a) HVL = 2.5 mmAl; Entrance Kerma = 0.10 cGy	
	mGy	rem
Thyroid	3.2E-02	3.2E-03
Eye/Brain	3.2E-02	3.2E-03
Ovaries	1.0E-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)	8.6E-02	8.6E-03
Skin	1.35E+00	1.35E-01

Time Period: pre-1970

Organ	Estimated dose (a) HVL = 2.5 mmAl; Entrance Kerma = 0.20 cGy	
	mGy	rem
Thyroid	3.48E-01	3.48E-02
Eye/Brain	6.4E-02	6.4E-03
Ovaries	2.5E-01 (b)	2.5E-02 (b)
Liver/gall bladder/spleen	9.02E-01	9.02E-02
Urinary Bladder	2.50E-01 (b)	2.50E-02 (b)
Colon/Rectum	2.50E-01 (b)	2.50E-02 (b)
Testes	5.00E-02 (b)	5.00E-03 (b)
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 (b)	2.50E-02 (b)
Bone marrow (male)	1.84E-01	1.84E-02
Bone marrow (female)	1.72-01	1.72-02
Skin	2.70E+00	2.70E-01

(a) as presented in ORAU 2003a

(b) Modified from Webster (1957) as presented in ORAU 2003a

Table 3.4.2-2 Organ dose estimates for AP and LAT lumbar Spine.[1] (1952-1974)

Organ	**AP lumbar spine[1]** HVL between 1.5 and 3.0 mm Al ESE Averaged 1.79 rad (rem)	**LAT lumbar spine** HVL between 1.5 and 3.0 mm Al ESE Averaged 5.79 rad (rem)
Thyroid	5.00E-04 (2.96)	1.00E-04 (1.90)
Eye / Brain	5.00E-04 (2.96)	1.00E-04 (1.90)
Ovaries	3.27E-01 (2.56)	2.25E-01 (2.10)
Urinary Bladder	3.27E-01 (2.56)	2.25E-01 (2.10)
Colon / Rectum	3.27E-01 (2.56)	2.25E-01 (2.10)
Testes[2]	2.55E-02 (3.10)	3.97E-02 (1.51)
Lung	1.22E-01 (2.53)	6.36E-02 (2.00)
Liver / Gall Bladder / spleen	1.22E-01 (2.53)	6.36E-02 (2.00)
Thymus	1.22E-01 (2.53)	6.36E-02 (2.00)
Esophagus	1.22E-01 (2.53)	6.36E-02 (2.00)
Stomach	1.22E-01 (2.53)	6.36E-02 (2.00)
Bone Surfaces	1.22E-01 (2.53)	6.36E-02 (2.00)
Remainder	1.22E-01 (2.53)	6.36E-02 (2.00)
Female Breast[3]	1.35E-00 (2.40)	1.37E-00 (1.90)
Uterus	4.36E-01 (2.60)	1.51E-01 (2.10)
Bone Marrow	5.75E-02 (2.60)	1.10E-01 (2.10)
Skin[2]	1.79E-00 (2.44)	5.79E-00 (1.84)

1. All doses are geometric means in rem and the values in parenthesis are the corresponding geometric standard deviations.
2. Calculated from information presented in Lincoln and Gupton (1958). Doses to the skin and testes represent measured rather than calculated doses.
3. ICRP 34 (1982) does not provide dose conversion factors for the breast for the lumbar spin view. The true dose is between the skin dose and the lung dose. The breast dose was calculated using the DCFs for the Chest AP and LAT examinations. This is a claimant favorable proxy for the dose to the breast.

Table 3.4.2-3 Organ Dose Estimates for Photofluorography, 1953 through 1968 (as presented in the Complex-Wide TIB, ORAU 2003a). Entrance Kerma = 3 cGy; HVL = 2.5 mmAl; all estimates are for uncollimated beams .

Organ	**View**	**Dose Conversion Factor (mGy per Gy air kerma) [a] HVL 2.5 mm Al**		**Organ Dose (rem)**
		Uncollimated		**Uncollimated**
Thyroid	PA	174 (b)		5.20E-1
Eye/Brain	PA	32		9.60E-2
Ovaries	PA	N/A		2.50E-2 (c)
Liver/Gall Bladder	PA	451		1.35E+0
Urinary Bladder	PA	N/A		2.50E-2 (c)
Colon Rectum	PA	N/A		2.50E-2 (c)
Testes	PA	N/A		5.00E-3 (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-1
Uterus	PA	N/A		2.50E-2 (c)
Bone Marrow (male)	PA	92		2.76E-1
Bone Marrow (female)	PA	86		2.58E-1
Skin (c)	PA			4.05E+00

a. Dose conversion Factors from Tables A.2 through A.9, ICRP Publication 34 (1982).

b. Dose Conversion Factor for AP C-spine, corrected for depth by 0.2 (ORAU 2003a).

c. Modified from Webster, as reported in ORAU 2003a.

Table 3.5-1. Doses to IREP Organs, adjusted for uncertainty of 30% PA Chest X-ray (rem)

Organ	June 11, 2001 to present (Type I)	1985 to June 4, 2001	1970 to 1985	Pre-1970
Skin	2.48E-02	9.10E-02	1.76E-01	3.51E-01
Thyroid	1.36E-03	5.07E-03	4.16E-03	4.52E-02
Eye & Brain	1.36E-03	5.07E-03	4.16E-03	8.32E-03
Ovaries	9.08E-05	3.38E-04	1.30E-04	3.25E-02
Liver/Gall Bladder	9.08E-05	4.38E-02	5.86E-02	1.17E-01
Urinary/Bladder	9.08E-05	3.38E-04	1.30E-04	3.25E-02
Colon/Rectum	9.08E-05	3.38E-04	1.30E-04	3.25E-02
Testes	1.75E-07	6.50E-07	1.30E-06	6.50E-03
Lungs (male)	1.10E-02	4.08E-02	5.45E-02	1.09E-01
Lungs (female)	1.18E02	4.38E-02	5.86E-02	1.17E-01
Thymus	1.18E-02	4.38E-02	5.86E-02	1.17E-01
Esophagus	1.18E-02	4.38E-02	5.86E-02	1.17E-01
Stomach	1.18E-02	4.38E-02	5.86E-02	1.17E-01
Bone Surface	1.18E-02	4.38E-02	5.86E-02	1.17E-01
Remainder		4.38E-02	5.86E-02	1.17E-01
Breast	2.03E-03	7.54E-03	6.37E-03	1.27E-02
Uterus (embryo)	9.08E-05	3.38E-04	1.69E-04	3.25E-02
Bone Marrow (male)	3.11E-03	1.16E-02	1.20E-02	2.39E-02
Bone Marrow (female)	3.00E-03	1.12E-02	1.12E-02	2.24E-02

* the higher of female or male estimates were used for thymus, esophagus, stomach, and bone surface.

Table 3.5-2. Doses to IRP Organs from Chest Photofluorography, 1953 to 1968 (rem). Adjusted for Uncertainty of 30%

Organ	View	Organ Dose (rem)	Adjusted Organ Dose (rem)
		Uncollimated	Uncollimated
Thyroid	PA	5.20E-1	6.76E-1
Eye/Brain	PA	9.60E-2	1.25E-1
Ovaries	PA	2.50E-2	3.25E-2
Liver/Gall Bladder	PA	1.35E+0	1.76E-2
Urinary Bladder	PA	2.50E-2	3.25E-2
Colon/ Rectum	PA	2.50E-2	3.25E-2
Testes	PA	5.00E-3	6.50E-3
Lungs (male)	PA	1.26E+00	1.64E+00
Lungs (female)	PA	1.35E+00	1.76E+00
Thymus	PA	1.35E+00	1.76E+00
Esophagus	PA	1.35E+00	1.76E+00
Stomach	PA	1.35E+00	1.76E+00
Bone Surfaces	PA	1.35E+00	1.76E+00
Remainder	PA	1.35E+00	1.76E+00
Breast	PA	1.47E-1	1.91E-1
Uterus	PA	2.50E-2	3.25E-2
Bone Marrow (male)	PA	2.76E-1	3.59E-1
Bone Marrow (female)	PA	2.58E-1	3.35E-1
Skin	PA	4.05E+00	5.27E+00

REFERENCES

Dean, A., 2003. "Regarding location of Rocky Flats X-ray documents," memorandum to file, October 21, MFG, Inc., Fort Collins, Colorado.

Decioneering Inc. 2000. Crystal Ball 2000 User Manual. Denver, Colorado.

Lopez, T., 2004, "Regarding discussion with T. Taulbee of OCAS concerning development of probability distributions for AP and LAT spine x-rays, January 23, MFG Inc., Fort Collins, Colorado.

ICRP (International Commission on Radiological Protection) 1982, *Protection of the Patient in Diagnostic Radiology*, Publication 34, Pergamon Press, New York, New York.

Lincoln, T.A. Gupton, E.D. 1958. "Radiation Doses in Diagnostic X-ray Procedures." Radiology. 71:208-215.

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 No. 102, NCRP, Bethesda, MD

OCAS (Office of Compensation Analysis and Support) 2002, *External Dose Reconstruction Implementation Guidelines*, Revision 1, OCAS-IG-001, National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention, U.S. Department of Health and Human Services, Washington, D.C.

ORAU (Oak Ridge Associated Universities) 2003a, *Technical Information Bulletin: Dose Reconstruction from Occupationally Related Diagnostic X-ray Procedures*, ORAUT-OTIB-0006, Oak Ridge, Tennessee. December 9, 2003.

ORAU (Oak Ridge Associated Universities) 2003b, *Technical Basis Document for the Savannah River Site*, ORAUT-TKBS-0003, Oak Ridge, Tennessee.

Public Law 106-398, *Energy Employees Occupational Illness Compensation Program Act of 2000*, (42 U.S.C. 7384 *et seq*.).

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

GLOSSARY

alloy: a substance composed of two or more metals blended together.

annual dose equivalent: the dose equivalent received in a year. The annual dose equivalent is expressed in units of rem (sievert).

alpha particles: positively charged particles of discrete energies emitted by certain radioactive materials; alpha particles expend their energy in short distances and will not penetrate the outer layer of skin; they are a significant hazard only when taken into the body where their energy Is absorbed in living tissue.

Atomic Energy Commission: original agency established for nuclear weapons and power production; a predecessor to the U.S. Department of Energy.

beta dose: a designation (also, beta) on some external dose records referring to the dose from less-energetic beta, x-ray and/or gamma radiation.

beta radiation: radiation consisting of charged particles of very small mass emitted spontaneously from the nuclei of certain radioactive elements. The beta particle is an electron moving at high velocity.

collective dose equivalent: the sum of the dose equivalents of all individuals in an exposed population. Collective dose is expressed in units of person-rem (person-sievert).

collective effective dose equivalent: the sum of the effective dose equivalents of all individuals in an exposed population. Collective effective dose is expressed in units of person-rem (person-sievert).

curie: a special unit of activity. One curie exactly equals 3.7×10^{10} nuclear transitions per second.

criticality: a self-sustaining nuclear fission reaction.

deep absorbed dose: the absorbed dose at the depth of 1.0 cm

deep dose equivalent (H_d): the dose equivalent at the respective depth of 1.0 cm in tissue.

detection limit (lower): the minimum quantifiable exposure or flux that can be detected.

dose equivalent (H): the product of the absorbed dose (D), the quality factor (Q), and any other modifying factors. The special unit is the rem. When D is expressed in Gy, H is in Sieverts (Sv). (1 Sv = 100 rem.)

dose of record: the dose files provided by DOE to NIOSH as part of an individual worker's files.

dosimeter: a device used to measure the quantity of radiation received. A holder with radiation-absorbing elements (filters) and an insert with radiation-sensitive elements packaged to provide a record of absorbed dose or dose equivalent received by an individual.

dosimetry: the science of assessing absorbed dose, dose equivalent, effective dose equivalent, from external and/or internal sources of radiation.

dosimetry system: a system used to assess dose equivalent from external radiation to the whole body, skin, and/or extremities. This includes the fabrication, assignment, and processing of the dosimeters as well as interpretation and documentation of the results.

exchange period (frequency): time period (weekly, biweekly, monthly, quarterly, etc.) for routine exchange of dosimeters.

exposure: expressed in roentgens (R): the ionization produced by photon (gamma and x-rays) radiation in air.

extremities: elbow through fingers; knee through toes.

field calibration: dosimeter calibration based on radiation types, intensity and energies present in the work environment.

film: generally means a film packet that contains one or more pieces of film in a light-tight wrapping. The film when developed has an exposure, caused by radiation, that can be measured using an optical densitometer.

film density: SEE optical density.

film dosimeter: a small packet of film within a holder.

fission: the splitting of an atomic nucleus, accompanied by the release of energy.

fissionable: material capable of undergoing fission (Pu-239, U-235, U-233).

flux, neutron (n/cm^2-sec): a measure of the intensity of radiation in neutrons/cm^2-sec. It is the number of neutrons passing through 1 square centimeter in 1 second.

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

gray: the international system unit of absorbed dose.

HEPA filter: high efficiency particulate air filter; a dense, corrugated filter capable of removing a high percentage of particulate material from an air flow

HEU: highly enriched uranium

hydrofluorination: chemical conversion to a form containing fluorine.

ionizing radiation: electromagnetic or particulate radiation capable of producing charged particles through interactions with matter.

isotope: elements having the same atomic number but different atomic weights; identical chemically but having different physical and nuclear properties

lumbrosacral spine: the five lumbar and five sacral vertebrae of the spine.

maximum permissible body burden (MPBB): whole body activity limit for a radionuclide.

maximum permissible lung burden, Pu (MPLB): the occupational limit for Pu; quantity of plutonium allowed in the chest at any given time.

minimum detectable activity (MDA): limit of detection for measurements; specific to types and energies of radiation and radioactive materials.

near-net shape: close to final shape.

neutron: neutral nuclear particle; mass nearly the same as the proton.

neutron, fast: neutrons with energy equal or greater than 10 keV.

neutron, intermediate: neutrons with energy between 0.5 eV and 10 keV.

neutron, thermal: neutrons in thermal equilibrium with surroundings. Generally, neutrons with energy less than about 0.5 eV.

neutron film dosimeter: a film dosimeter that contains an Neutron Track Emulsion, type A, film packet.

Nuclear Emulsion: often referred to as “NTA” film and used to measure personnel dose from neutron radiation.

Nuclear Track Emulsion, Type A (NTA): a film that is sensitive to fast neutrons. The developed image has tracks caused by neutrons that can be seen by using appropriate imaging capability.

open window (OW): designation on film dosimeter reports that implies the use of little (i.e., only security credential) shielding.

operating area: designation of major operational work areas onsite.

optical density: the quantitative measurement of photographic blackening: density defined as $D = \mathrm{Log}_{10} (I_o/I)$.

pencil dosimeters: a type of ionization chamber used by personnel to measure radiation dose. Used by visitors or under other conditions of short-term exposure where data should be evaluated immediately. Results may be labeled as “Pen” dose. Other names: pencil, pocket dosimeter, pocket pencil, pocket ionization chamber.

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: a unit or "particle" of electromagnetic radiation consisting of x- and/or gamma rays.

photon (ionizing): x- or gamma radiation.

photon - x-ray: electromagnetic radiation of energies between 10 keV and 100 keV whose source can be x-ray machine or radioisotope.

pit: nuclear weapon core, made of fissionable material

quality factor, Q: a modifying factor used to derive dose equivalent from absorbed dose.

radiation: alpha, beta, neutron, x- or gamma radiation.

radioactivity: the spontaneous emission of radiation from unstable nuclei.

radionuclide: a radioactive isotope of an element, identified by atomic number and atomic weight

relative biological effectiveness (RBE): a ratio of absorbed dose of a reference radiation to absorbed dose of a other radiation producing the same biological effects

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

rep: roentgen-equivalent-physical (mrep = millirep) used when reporting beta exposures.

Roentgen (R or 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.

shallow absorbed dose (D_s): the absorbed dose at a depth of 0.007 cm in a material of specified geometry and composition.

shallow dose equivalent (H_s): dose equivalent at a depth of 0.007 cm in tissue.

shielding: any material or obstruction that or attenuates radiation and thus can protect personnel or materials from radiation.

sievert (Sv): the SI unit for dose equivalent. (1 Sv = 100 rem.)

silver shield(s): the 1-mm thick shields covering a portion of the film packet in early film dosimeters.

site returns: weapons components retired and returned for disassembly and recovery of materials

skin dose: absorbed dose at a tissue depth of 7 mg/cm^2.

Snoopy: portable neutron monitoring instrument with a moderated BF_3 detector.

thermoluminescent: property of a material that causes it to emit light as a result of being excited by heat.

thermoluminescent dosimeter (TLD): a holder containing solid chips of material that when heated will release, as light, energy stored during interaction with ionizing radiation. The measurement of the emitted light is proportional to absorbed dose.

transuranic: an element with an atomic number greater than uranium (92); all transuranic elements are radioactive and are produced artificially.

trigger: fissionable core of nuclear weapon, also used to trigger fusion energy release

whole body dose: commonly defined as the absorbed dose at a tissue depth of 1.0 cm (1000 mg/cm^2); however, this term is also used to refer to the recorded dose.

x-ray: ionizing electromagnetic radiation produced outside the nucleus.