Document Title: Lawrence Livermore National Laboratory – Occupational Medical Dose	Document Number: ORAUT-TKBS-0035-3 Revision: 00 PC-1 Effective Date: 10/26/2005 Type of Document: TBD Supersedes: None

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Approval:	Signature on File James W. Neton, Associate Director for Science	Approval Date:	08/22/2005

☐ New ☐ Total Rewrite ☐ Revision ☒ Page Change

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PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
08/22/2005	00	New technical basis document for the Lawrence Livermore National Laboratory – Occupational Medical Dose. First approved issue. Initiated by Jay J. Maisler.
10/26/2005	00 PC-1	First approved page change. Page change initiated to incorporate recent direction from NIOSH to include DOL review comments on page 5. No sections were deleted. Retraining is not required. Initiated by Jay J. Maisler. Approval: Signature on File 10/14/2005 Jay J. Maisler, TBD Team Leader Signature on File 10/13/2005 Judson L. Kenoyer, Task 3 Manager Signature on File 10/16/2005 Richard E. Toohey, Project Director Signature on File 10/26/2005 James W. Neton, Associate Director for Science

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ACRONYMS AND ABBREVIATIONS

cm	centimeter
DCF	dose conversion factor
DOE	U.S. Department of Energy
ESE	entrance skin exposure
FDA	Food and Drug Administration
Gy	gray
ICRP	International Commission on Radiological Protection
in.	inch
IREP	Interactive RadioEpidemiological Program
keV	kiloelectron-volt (1,000 electron volts)
kVp	kilovolts-peak
LLNL	Lawrence Livermore National Laboratory
mA	milliampere
mm	millimeter
mR	milliroentgen
mrad	millirad
NCRP	National Council on Radiation Protection and Measurements
PA	posterior-anterior
R	roentgen
s	second
SID	source-to-image distance
SSD	source-to-skin distance
U.S.C.	United States Code

3.1 INTRODUCTION

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

In this document the word "facility" is used as a general term for an area, building, or group of buildings that served a specific purpose at a site. It does not necessarily connote an "atomic weapons employer facility" or a "Department of Energy [DOE] facility" as defined in 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 [probability of causation] guidelines established under subsection (c) …." [42 U.S.C. § 7384n(b)]. Neither the statute nor the probability of causation guidelines (nor the dose reconstruction regulation) define "performance of duty" for DOE employees with a covered cancer or restrict the "duty" to nuclear weapons work.

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

Since beginning in 1952, chest X-ray examinations have been prescribed by Health Services Department clinicians at Lawrence Livermore National Laboratory (LLNL). In addition to exposure of the lungs, other tissues of the body are irradiated by the primary X-ray beam and by scattered and leakage photons. This document develops claimant-favorable estimates of doses from occupational medical X-rays to the lungs and other organs of the body. These doses, determined for chest examinations during different periods at LLNL, are based on the operating parameters of the machines and the conditions of exposure, insofar as these are known.

3.2 REQUIRED MEDICAL X-RAYS

Existing documents do not furnish a complete record of the specific criteria used since 1952 to determine either which workers were required to have X-ray examinations or the frequencies of the examinations. This summary is based on record searches and discussions with present and former staff members of the Health Services Department of LLNL.

From 1952 until about 1993, baseline X-rays were required for all pre-employment evaluations. In August of 1990, a Food and Drug Administration (FDA) survey of the medical X-ray program at LLNL provided the following recommendation: "Chest radiographs were indicated to be routinely performed as a requirement for employment at the facility. Documentation should present the reasons for this routine procedure. Chest radiographs are apparently not done as a routine part of regular or periodic examinations" (Van Pelt 1990).

LLNL Health Services Department Radiography Program, March 1991, provides the following information (LLNL 1991):

> *Requisition of X-ray studies for the purpose of diagnostic information should be based on clinical evaluation. Diagnostic X-ray examinations will be requested after an appropriate medical history and physical examination has been performed, in accordance with reasonable medical practice and occupational guidelines. Diagnostic objective, relevant medical history and X-ray procedure requested will be recorded on the radiographic request form. … Based on the unique nature of the work performed at LLNL, a pre-employment baseline PA [posterior–anterior] chest X-ray examination is required. This film may be done at the time of pre-employment examination or a copy of a previous film or report may be requested and kept on file. Medical surveillance programs may mandate periodic chest X-rays. Periodic chest X-ray examinations unrelated to job exposure will not be done routinely but may be ordered by the examiner if clinically indicated*.

Detailed records were made for all X-ray examinations. The records include identification of the individual, the type of examination, data on operating parameters for the procedure, and other pertinent information. It appears that a single PA chest projection was standard practice. Radiographs are archived at LLNL and can be consulted. There is no evidence that fluoroscopy was ever used at LLNL for required medical examinations. A random sample of X-ray portfolios was selected from the archives and examined for seven individuals employed at LLNL in the 1950s and 1960s. No small-format films were found.

Apart from the pre-employment baseline PA chest X-ray, it does not appear that LLNL mandated routine examinations on a regular basis for employees. Chest films for beryllium and asbestos workers were apparently introduced in the 1980s with a frequency dependent on the age and exposure of the individual (Noonan 2002). Available documents indicate that chest X-rays were administered on an individual basis in keeping with acceptable guidelines of occupational medicine. In the absence of a general policy for frequencies of regularly required chest X-rays, it is not feasible to address the three general dose reconstruction approaches (maximizing, best estimate, and minimizing) specified in *Occupational X-Ray Dose Reconstruction for DOE Sites* (ORAUT 2004). Dose reconstructors must consult an employee's medical records to determine the extent of the worker's required medical X-rays.

3.3 EQUIPMENT AND TECHNIQUES

Table 3-1 lists the diagnostic medical X-ray units used at LLNL, as well as can be determined from existing records. Reported data were found and are included for entrance skin exposures (ESE) for PA chest examinations with all three systems. The earliest document (Graham and Williams 1975) describes results of an in-house radiation survey of the Fisher X-ray machine in the Medical Department by the LLNL Health Physics Group. Measurements gave an ESE of 19 mR [at a source-to-skin distance (SSD) of 157 cm], for a "typical" chest radiograph (100 kVp, 100 mA, 1/20 s). Beam collimation was deemed "satisfactory," although the position of the light spot used for centering needed correction. The results of the survey indicated that the facility was operating properly and had adequate shielding. No other information was found about other aspects of the facility, such as screens, grids, film types, and development parameters.

Table 3-1. LLNL X-ray equipment.

Period	Equipment and nominal operating parameters
1952–Dec. 1980	Fisher X-ray machine: 100 kVp, 100 mA, 1/20 s, normal filtration (3 mm Al), effective energy 32 keV, "satisfactory" collimation, measured ESE = 19 mR at SSD = 157 cm (Graham and Williams 1975)
Jan. 1981–Oct. 1990	Xonics: Stationary general purpose X-ray system, phototiming, Kodak M-35 film processor using Kodak XRP chemistry, blue-light sensitive film, measured ESE = 45 mR (Van Pelt 1990)
Nov. 1990–Sept. 1992	Upgraded Xonics system: Blue-light sensitive film replaced with green-light sensitive Kodak T-MAT G and T-MAT L films, new cassette holders with compatible emitting screens, manual control techniques applied, measured ESE = 11 to 15 mR (Winstanley 1990a,b; Noonan 1991; Thomas 1991)
Oct. 1992–present	Bennett: Stationary general purpose radiographic system, Kodak M35A X-OMAT film processor, Lanex Regular screens, ESE = 12 mR (Thomas 1993) to 14 mR (Miles 1999); also 110 kVp, 200 mA, 0.017 s, ESE = 14 mR (LLNL 2004)

The Fisher system was replaced by a Xonics general purpose radiographic unit some time around 1980, although it is not clear precisely when. The only survey report found for the Fisher unit (Myers and Williams 1979) compares design features with those recommended by the National Council on Radiation Protection and Measurements (NCRP) and by the State of California. The earliest document found that pertains to the Xonics unit is a letter dated July 9, 1985 (Shingleton 1985). Therefore, the replacement of the Fisher by the Xonics machine must have occurred between these last two dates. A later report (Thomas 1991) on an FDA survey at LLNL on August 28 and 29, 1991, parenthetically mentions that the Xonics system control/generator was manufactured in 1980. Therefore, based on these dates, the organ doses given in this document for the period from 1952 through December 1980 are for the Fisher machine and those for January 1981 through September 1992 are for the Xonics machine.

In the 1980s, a formal interagency agreement between the U.S. Department of Energy (DOE) and the FDA was established to conduct periodic surveys of government-owned, contractor-operated diagnostic X-ray equipment (Davis 1987). The surveys at LLNL were conducted by FDA. They covered the physical equipment itself as well as operational and administrative procedures. A series of specific recommendations was made by FDA following their survey on August 15, 1990 (Van Pelt 1990). A principal objective, among others, was to reduce the ESE for a chest radiograph from the measured value of 45 mR. A number of modifications were made to the Xonics system to upgrade the technique for chest X-rays, as summarized in the third row of Table 3-1. The ESE was reduced to the range of 11 to 15 mR (Winstanley 1990b, Thomas 1991). With the alterations, the estimated organ doses for examinations with the Xonic machine were substantially reduced to lower values as of November 1990 (Noonan 1991).

The Bennett X-ray machine was installed at LLNL in September 1992 (Higginson 1992), replacing the Xonics unit, and it is still in use today. The new system underwent a complete, in-depth survey by FDA on October 27, 1992 (Thomas 1993). All items tested were within federal specifications. The estimated ESE with automatic exposure control was reported as 12.15 mR for a PA chest exam. Over time, values of ESE in the range 12 to 14 mR were reported (Table 3-1).

Quality assurance has been verified regularly by in-house surveys and by FDA visits. The interagency agreement between DOE and FDA was concluded around the end of the 1990s. Since then LLNL has continued to have annual outside reviews performed under contract.

Repeat or retake studies have been conducted. There is no indication of any significant repeat rate.

3.4 ORGAN DOSE CALCULATIONS

3.4.1 Basis and Methodology

With the exception of that for the skin, estimations of the mean dose equivalents to individual organs of the body from a given X-ray exposure are based on dose conversion factors (DCFs) provided in Publication 34 of the International Commission on Radiological Protection (ICRP 1982). Skin doses are obtained by using backscatter factors from Table B.8 of NCRP (1989). Tables of DCFs are given in ICRP (1982) for seven organs in an adult anthropomorphic phantom for a number of common radiographic examinations with beams of different quality. For the PA chest projection, a source-to-image distance (SID) of 183 cm (72 in.) and an image receptor size of 35.6 × 43.2 cm (14 × 17 in.) are used. For an organ not included in ICRP (1982), but needed for the Interactive RadioEpidemiological Program (IREP), the DCF is taken to be that for the anatomically closest organ in the ICRP tables. Table 3-2 lists the ICRP reference organs for the IREP analogues (ORAUT 2003). When the reference organ is the lung, different values of the organ doses are given in ICRP (1982) for males and females. The larger of the two values is assigned for the dose equivalent to the IREP organ analogue.

Table 3-2. Analogues for IREP organs not included in ICRP Publication 34 (ICRP 1982).

Anatomical location	ICRP Publication 34 reference organ	IREP organ analogue
Thorax	Lung	Bone surfaces Esophagus Liver/gall bladder/spleen Remainder organs Stomach Thymus
Abdomen	Ovaries	Colon/rectum Urinary/bladder
Head and neck	Thyroid	Eye/brain

The ICRP tables were developed under the assumption that the primary X-ray beam is collimated to the image receptor size. The application of these DCF tables to the early X-ray machines, particularly before about 1970, must therefore be made in a way that compensates for the lack of collimation. Claimant-favorable allowance for this circumstance during different periods in the past, based on ICRP (1982), has been assessed in the generic document by ORAUT (2003), which will be applied to estimate doses from the Fisher machine. In addition, when other data are not available, ORAUT (2003) recommends that the following values be used to express beam quality in terms of the half-value layer of Al: 2.5 mm prior to 1980 and 4.0 mm for subsequent years. The ICRP (1982) values

are used directly to obtain the organ doses for examinations with the Xonics and Bennett systems in Table 3-1.

The ICRP DCFs are provided for an SID of 183 cm (72 in.) and an image-receptor size of 35.6 × 43.2 cm (14 × 17 in.). Allowing 5 cm for a cassette thickness and 26 cm for the average chest thickness for a PA view implies an SSD of 152 cm (60 in.). Of the seven organs in ICRP (1982), separate doses for males and females are given for the active bone marrow and the lungs.

The ICRP DCFs give the average dose equivalent in a given organ in milligray for different beam qualities when the entrance kerma (air kerma in air without backscatter) is 1-Gy. In what follows, the approximation will be made that an ESE of 1 R produces a skin entrance kerma of 1 rad (ORAUT 2003). In addition to simplifying the computations, this assumption is well within relatively large uncertainties from other sources and is claimant-favorable.

Table 3-3 lists the resultant organ dose equivalents for the periods during which each X-ray system was in use. The following sections discuss each system.

3.4.2 Fisher Machine

No information about the Fisher X-ray system prior to the 1975 survey by Graham and Williams was found. Their survey reported a measured ESE of 19 mR with an SSD of 157 cm. For the smaller value used in the present document (SSD of 152 cm), the ESE is 19 mR × $(157/152)^2$ = 20 mR = 0.020 R. The skin entrance kerma is thus 0.020 rad. In the absence of earlier documentation, the pre-1970 default values for organ doses given in Table 3-3 for the period 1952 through December 1969 are taken from Table 4.0-1 of ORAUT (2003). For January 1970 through December 1980, when the Fisher machine was probably retired, the doses in Table 3-3 are based on the default values from ORAUT (2003) for this time period and scaled to be consistent with the 1975 measurements of Graham and Williams. Since the latter work showed the entrance kerma to be 0.020 rad and the default value is 0.10 rad for this time period, the doses given in column three of Table 3-3 are scaled to one-fifth their respective values in Table 4.0-1 of ORAUT (2003).

3.4.3 Xonics System

The Xonics system replaced the Fisher unit around January 1981, and it operated through about September 1992. Although there is somewhat more information available for it than for the Fisher system, the number of documents is limited. However, reports from an FDA survey on August 15, 1990 (Van Pelt 1990), and from the follow-up by LLNL (Noonan 1991) provide considerable detailed information. The survey tested an array of items and resulted in a number of suggested action items. One concern was the finding that the ESE measured with a phantom for chest X-rays was 45 mR. Subsequent improvements upgraded the Xonics system in a number of ways, as noted in Table 3-1. The ESE was reduced to a reported range of 11 mR to 15 mR (Winstanley 1990a,b), which was verified by the FDA survey of the following year (Thomas 1991).

No measurements were located that document the ESE for the Xonics chest exams at earlier times, from its beginning in January 1981 until the August 15, 1990, survey. In the absence of data to the contrary, the claimant-favorable assumption is made that the ESE was 0.045 R and the skin entrance kerma was 0.045 rad for the entire second period in Table 3-1. Thereafter, from November 1990 until its replacement after September 1992, the ESE is assumed to be 0.015 R and the entrance kerma, 0.015 rad. No records were found in which this level was exceeded. Table 3-3 lists the organ doses using these two values for the kerma and ICRP (1982).

Table 3-3. Organ dose equivalents (rem) at different times for 14- × 17-in. PA chest radiography.

Organ	Dose equivalent (rem)				
	1952-Dec 1969 Fisher ESE=0.20 R	Jan 1970-Dec 1980 Fisher ESE = 0.020 R	Jan 1981-Oct 1990 Xonics ESE = 0.045 R	Nov 1990-Sep 1992 Xonics ESE = 0.015 R	Oct 1992-present Bennett ESE = 0.014 R
Bone marrow (active)	Male 1.8E-2 Female 1.7E-2	Male 1.8E-3 Female 1.7E-3	Male 8.0E-3 Female 7.7E-3	Male 2.7E-3 Female 2.6 E-3	Male 2.5E-3 Female 2.4E-3
Bone surfaces	9.0E-2	9.0E-3	3.0E-2	1.0E-2	9.4E-3
Breast (female)	9.8E-3	9.8E-4	5.2E-3	1.7E-3	1.6E-3
Colon/rectum	2.5E-2	2.0E-5	2.3E-4	7.8E-5	7.3E-5
Esophagus	9.0E-2	9.0E-3	3.0E-2	1.0E-2	9.4E-3
Eye/brain	6.4E-3	6.4E-4	3.5E-3	1.2E-3	1.1E-3
Liver/gall bladder/spleen	9.0E-2	9.0E-3	3.0E-2	1.0E-2	9.4E-3
Lungs	Male 8.4E-2 Female 9.0E-2	Male 8.4E-3 Female 9.0E-3	Male 2.8E-2 Female 3.0E-2	Male 9.4E-3 Female 1.0E-2	Male 8.8E-3 Female 9.4E-3
Ovaries	2.5E-2	2.0E-5	2.3E-4	7.8E-5	7.3E-5
Remainder	9.0E-2	9.0E-3	3.0E-2	1.0E-2	9.4E-3
Stomach	9.0E-2	9.0E-3	3.0E-2	1.0E-2	9.4E-3
Testes	5.0E-3	2.0E-7	4.5E-7	1.5E-7	1.4E-7
Thymus	9.0E-2	9.0E-3	3.0E-2	1.0E-2	9.4E-3
Thyroid	3.5E-2	6.4E-4	3.5E-3	1.2E-3	1.1E-3
Urinary/bladder	2.5E-2	2.0E-5	2.3E-4	7.8E-5	7.3E-5
Uterus (embryo)	2.5E-2	2.6E-5	2.3E-4	7.8E-5	7.3E-5
Skin	2.7E-1	2.7E-2	6.3E-2	2.1E-2	2.0E-2

3.4.4 Bennett System

The FDA performed a survey of the Bennett X Ray Company system on October 27, 1992 (Thomas 1993). A large number of items were checked, and all were verified to be within federal specifications. Under automatic exposure control, the ESE was reported to be 12.15 mR for a PA chest X-ray. Records show that the Bennett system has operated satisfactorily. An FDA survey on September 9, 1999, measured an ESE of 14 mR for PA chest exposures with a phantom (Miles 1999). The ESE value of 0.014 R, which was also determined recently (LLNL 2004), was assumed for the Bennett system, which operated from October 1992 to the present. Table 3-3 lists the resultant organ doses with the entrance kerma of 0.014 rad.

3.5 UNCERTAINTY

Uncertainties in the required occupational medical X-ray organ doses have been analyzed in ORAUT (2003). The document considers several major sources of uncertainty: measurement errors; variations in applied voltage (peak voltage), beam current, and exposure time; and uncertainties due to patient size and placement. ORAUT (2003) assesses the relative error in an individual ESE or organ dose to be ±30% at 1 standard deviation. For claimant-favorable adjustment, it is estimated that the actual doses could have been up to 30% larger than those given in Table 3-3.

3.6 DOSE RECONSTRUCTION

Table 3-3 lists the claimant-favorable best estimates of the organ dose equivalents for a PA chest X-ray. The uncertainty analysis indicates that actual doses would not likely exceed 1.3 times those values in individual cases.

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GLOSSARY

absorbed dose
Energy absorbed per unit mass; units are rad and gray.

backscatter
Radiation that is scattered backwards, enhancing skin dose in areas where X-ray beam enters the body.

dose equivalent
Product of absorbed dose and a quality factor or radiation weighting factor. With absorbed dose in rad, unit is rem.

exposure
Amount of electric charge produced per unit mass of air by electromagnetic radiation.

gray (Gy)
Unit of absorbed dose, defined as 1 joule per kilogram. It is equal to 100 rad.

kerma
Sum of initial kinetic energies of all charged particles (including Auger electrons) liberated by uncharged radiation per unit mass. Units are rad and gray. The word derives from *kinetic energy released per unit mass*.

primary X-rays
X-rays that constitute the useful beam that emerges from the tube.

rad
Unit of absorbed dose, defined as 100 ergs per gram. It is equal to is 0.01 Gy.

rem
Unit of dose equivalent.

roentgen
Unit of exposure.

secondary X-rays
As distinct from primary X-rays, secondary X-rays are those that are scattered from objects or leak from the source assembly.

X-ray
(1) Electromagnetic radiation emitted by fast electrons slowing down in matter or in certain electronic transitions in atoms. (2) A radiograph produced by X-rays.