DOE Review Release 02/17/2021

Summary Site Profile for Sandia National Laboratories in Livermore, California

ORAUT-TKBS-0053 Rev. 02
Effective Date: 01/13/2021
Supersedes: Revision 01

Subject Expert(s): Lawrence A. Page, Jr.

Document Owner Approval:	Signature on File Lawrence A. Page, Jr., Document Owner	Approval Date:	01/09/2021
Concurrence:	Wade C. Morris Signature on File for John M. Byrne, Objective 1 Manager	Concurrence Date:	01/11/2021
Concurrence:	Signature on File Scott R. Siebert, Objective 3 Manager	Concurrence Date:	01/10/2021
Concurrence:	Vickie S. Short Signature on File for Kate Kimpan, Project Director	Concurrence Date:	01/12/2021
Approval:	Signature on File Timothy D. Taulbee, Associate Director for Science	Approval Date:	01/13/2021

FOR DOCUMENTS MARKED AS A TOTAL REWRITE, REVISION, OR PAGE CHANGE, REPLACE THE PRIOR REVISION AND DISCARD / DESTROY ALL COPIES OF THE PRIOR REVISION.

☐ New ☒ Total Rewrite ☐ Revision ☐ Page Change

PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
05/01/2007	00	Approved new summary site profile for Sandia National Laboratories in Livermore, California. No meetings with union members have been held to date. Incorporates formal internal and NIOSH review comments. Attributions and Annotations section added. There is an increase in assigned dose and a PER is required. Training required: As determined by the Task Manager. Initiated by Laura McDowell-Boyer.
04/28/2014	01	Revision initiated to update the document with new information. Modified Sections 1.0, 5.0, and 6.0 to incorporate the Special Exposure Cohort class through 1994, including references to SEC-ER and HHS designation letter. Replaced reference to ORAUT-TKBS-0048, *Site Profile for the Brookhaven National Laboratory*, with ORAUT-TKBS-0036-6, *Argonne National Laboratory-East – External Dosimetry*. Added information pertaining to chronic lymphocytic leukemia to Section 3.3 and added Table 3-6. Amended Section 5.2 to eliminate the sentence that only tritium and uranium were of concern, and stating there were limited bioassay data for tritium and uranium. Changed Section 5.7 to reflect that unmonitored internal dose is only applicable post-SEC, to indicate applicable years based on facility decommissioning, to remove all references to maximum permissible concentrations, and to supply uranium intake information for all solubilities. Altered Table 5-5 to remove the row related to 1959 and to change the "1990s" row to "post-1994." Adjusted Table 5-8 for consistency with Table 5-2, to account for tritium intake through skin absorption, and to address uranium tritides, adding ORAUT-OTIB-0066 as a reference. Included an instruction for dose reconstructors to use minimum detectable activities as provided in the records when available. Incorporates formal internal and NIOSH review comments. Training required: As determined by the Objective Manager. Initiated by Lawrence A. Page, Jr.
01/13/2021	02	Revision initiated to update the document with new information related to a revision of ORAUT-OTIB-0006, *Dose Reconstruction from Occupational Medical X-Ray Procedures*, and the implementation of ORAUT-OTIB-0088, *External Dose Reconstruction.* Included information for skin doses to various areas from posterior-anterior and lateral chest X-rays in Table 3-5, and from lumbar spine examinations in Table 3-7. X-ray doses and computational information in Tables 3-1, 3-2, and 3-4, which had previously been labeled "Pre-1970" were renamed to include the year 1970. Information and doses in the tables previously labeled "1970–1985" were changed to reflect the period "1971–1975." Skin dose information in Table 3-4 for 1986 to present were changed to reflect the revision of the backscatter factor from ORAUT-OTIB-0006.

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
01/13/2021	02 (continued)	Revision updated to upgrade the document with new and corrected environmental data, both internal and external. Previously unavailable reference documents from Lawrence Livermore National Laboratory were employed to reevaluate existing environmental data and to provide additional data for the period 2004 to 2018. Updated uncertainty information regarding medical dose with information from the International Vocabulary of Metrology (JCGM 2008). Included information and corrections regarding NTA film badges. Incorporates formal internal and NIOSH review comments. Constitutes a total rewrite of the document. Training required: As determined by the Objective Manager. Initiated by Lawrence A. Page, Jr.

TABLE OF CONTENTS

SECTION **TITLE** **PAGE**

Acronyms and Abbreviations 8

1.0 Introduction 11
1.1 Purpose 12
1.2 Scope 12
1.3 Special Exposure Cohort 12

2.0 Site Description 12
2.1 Introduction 12
2.1.1 Purpose 12
2.1.2 Scope 12
2.1.3 Background 13
2.2 Site Activities 14
2.2.1 Tritium Research Laboratory 18
2.2.2 Depleted Uranium Machining 19
2.2.3 Radiography, Accelerators, and Neutron Generators 19
2.3 Site Processes 20
2.3.1 Incidents 20
2.3.2 Effluents 21
2.4 Radiological Protection and Access Control 21

3.0 Occupational Medical Dose 22
3.1 Examination Frequency 23
3.2 Equipment and Techniques 23
3.3 Organ Dose Estimates 24
3.3.1 Parameters and Estimation Method 24
3.3.2 Organ Dose Estimates 27
3.4 Uncertainties 27

4.0 Occupational Environmental Dose 32
4.1 Introduction 32
4.1.1 Purpose 32
4.1.2 Scope 33
4.2 Internal Dose from Onsite Atmospheric Radionuclide Concentrations 33
4.2.1 Radionuclides of Concern 33
4.2.2 Source Terms for Internal Dose 35
4.2.3 Annual Intake of Radioactivity 35
4.2.3.1 Inhalation Intakes 35
4.3 External Exposure to Onsite Atmospheric Radionuclide Concentrations 38
4.3.1 Locations of Concern 38
4.3.2 Gamma-Emitting Radionuclides 39
4.3.3 Neutron Exposure 42

5.0 Internal Dosimetry 44
5.1 Introduction 44
5.1.1 Purpose 44
5.1.2 Scope 44
5.1.3 Special Exposure Cohort 44
5.2 Summary of Potential Internal Radionuclide Exposures 45

5.2.1 Tritium Research Laboratory 45
5.2.2 Uranium Alloy Machining 45
5.3 Bioassay Programs 46
5.3.1 Tritium Bioassay Programs 46
5.3.2 Uranium Bioassay Programs 47
5.4 Bioassay Laboratory Procedures and Minimum Detectable Intakes 47
5.4.1 Tritium 47
5.4.2 Uranium 49
5.5 Bioassay Results 50
5.6 Method of Calculating Dose from Urine Bioassay Data 50
5.7 Airborne Radionuclide Concentrations 51
5.8 Unmonitored Dose Estimates 52
5.9 Radiation Dosimetry Reports 52
5.10 Summary Tables 53

6.0 Occupational External Dose 54
6.1 Introduction 54
6.1.1 Purpose 54
6.1.2 Scope 54
6.1.3 Special Exposure Cohort 54
6.2 Background 54
6.3 Dose Reconstruction Parameters 55
6.3.1 Site Historical Administrative Practices 55
6.3.1.1 Administrative Practices Before 1989 55
6.3.1.2 Administrative Practices After 1989 56
6.3.2 Site Dosimetry Technology 58
6.3.2.1 Dosimetry Technology, 1956 to 1988 58
6.3.2.2 Dosimetry Technology, 1989 to Present 59
6.3.3 Calibration 60
6.3.3.1 Calibration for Dosimeter Technologies, 1965 to 1988 60
6.3.3.2 Calibration for Dosimeter Technologies, 1989 to Present 61
6.4 Dose Calculation and Reporting 61
6.4.1 Dose Calculation and Reporting, 1956 to 1988 61
6.4.2 Dose Calculation and Reporting, 1989 to Present 62
6.4.3 Exposure Energy Spectra 65
6.4.3.1 Neutron Dose Conversion Factors 67
6.4.4 Missed Dose 68
6.4.5 Organ Dose Conversion Factors 68
6.4.6 Adjustments to Recorded Neutron Dose 68
6.4.6.1 Correction for Low-Energy Neutrons with NTA Neutron Dosimeters 69
6.4.6.2 Angular Dependence of NTA Neutron Dosimeters 69
6.4.6.3 Track Fading of Neutron NTA Dosimeters 69
6.4.7 Uncertainty 69

7.0 Attributions and Annotations 70

References 71

Glossary 93

ATTACHMENT A SUMMARY OF ACTIVITIES AT SITE BUILDINGS 96

ATTACHMENT B DOSIMETRY PROGRAM ADMINISTRATIVE DOCUMENTATION EXAMPLES 99

LIST OF TABLES

TABLE	TITLE	PAGE
2-1	Area information and parameters	16
2-2	Historical T_2 inventory at TRL	18
2-3	Effluents of ^{3}H to air and sewer during operations and cleanup of TRL	21
3-1	Entrance kerma by procedure and period	25
3-2	DCFs; absorbed dose for organs at various Al HVL for radiography	26
3-3	Organs without ICRP Publication 34 DCFs and their substitutes	27
3-4	Organ dose estimates for chest X-rays	28
3-5	Skin area dose estimates from chest X-rays	28
3-6	Organ doses from lumbar spine X-ray, 1956 to 1971	30
3-7	Skin doses from lumbar spine X-ray, 1956 to 1971	30
3-8	Distributions and corresponding statistical parameters for the dose to the B-lymphocytes	31
4-1	Summary of methodology for estimating intakes of ^{3}H, ^{234}U, and ^{239}Pu	35
4-2	Sitewide annual median inhalation intakes, 1956 to 1970	36
4-3	Sitewide annual median inhalation intakes, 1971 to 2018	36
4-4	External gamma radiation dose based on 2,500 hr/yr exposure duration	41
4-5	Elevated neutron dose due to LLNL perimeter neutron source, based on 2,500 hr/yr exposure duration	43
5-1	MDAs for and frequency of tritium bioassay	48
5-2	Preliminary timeline for uranium in urine analyses	50
5-3	Range of tritium doses based on bioassay, 1979 to 1981	50
5-4	Estimated tritium doses based on bioassay, 1982 to 1995	51
5-5	DAC values for tritium and uranium	52
5-6	Internal dose control program	53
5-7	Detection limits for urine bioassay for ^{3}H with LSC	53
5-8	Detection limits for total uranium bioassay	53
5-9	Facility, source, solubility type, and particle size	54
6-1	Documented dosimetry technologies and dose quantities	58
6-2	Monthly and quarterly LLDs for the Harshaw Model 8802 dosimeter card	65
6-3	Selection of radiation energies and percentages	66
6-4	Neutron DCFs for applicable SNL-CA facilities	67
6-5	Estimated maximum annual missed photon, beta, and neutron dose	68
6-6	Dose units for organ DCFs	68
6-7	Systematic uncertainty estimates	69
A-1	Summary of activities by building	96

LIST OF FIGURES

FIGURE	TITLE	PAGE
2-1	Boundaries of SNL-CA property	14
2-2	Map of SNL-CA facilities	15
3-1	Kerma in air at 1 m from X-ray source as a function of total filtration for various values of tube potential	25
4-1	TLD locations since 1989	39
4-2	Location of LLNL perimeter gamma and neutron dosimeters	40
4-3	Location of LLNL offsite gamma dosimeters	40
4-4	Livermore valley radiation background measurements in comparison with annual average measurements at LLNL site perimeter and LLNL Site 300	42
6-1	ALARA reporting action levels	56
6-2	Harshaw Model 8812 dosimeter assembly, element specifications, and respective radiation and dose equivalent quantities	60
6-3	Example Harshaw 8800 card reader calibration procedures, forms, analysis, and output	62
6-4	Example calibration form for the Harshaw 4000 dosimetry system	63
6-5	Angular dependence testing results for the Harshaw 8800/8812 dosimetry system.	64
B-1	Example external dosimetry history records (output from SANDOS)	100
B-2	Example nonroutine dosimeter evaluation form for special radiation work case (potential neutron exposures)	101
B-3	Example nonroutine dosimeter evaluation form for special radiation work case (potential neutron exposures)	102
B-4	Example unreturned dosimeter investigation report	103
B-5	Example unreturned dosimeter questionnaire follow-up letter	104
B-6	Example portion of unreturned dosimeter questionnaire showing various codes used by the Personnel Dosimetry Division	105
B-7	Work Area Radiation Dosimetry Request Form	106
B-8	Example work area radiation dosimetry results report	107

ACRONYMS AND ABBREVIATIONS

AEC	U.S. Atomic Energy Commission
ALARA	as low as is reasonably achievable
AP	anterior-posterior
AWE	Atomic Weapons Employer
Bq	becquerel
CEDE	committed effective dose equivalent
CEP	Controls for Environmental Pollution
CFR	Code of Federal Regulations
cGy	centigray
Ci	curie
cm	centimeter
cpm	counts per minute
CRDL	Chemical and Radiation Detection Laboratory
d	day
DAC	derived air concentration
DCF	dose conversion factor
DOE	U.S. Department of Energy
DOELAP	DOE Laboratory Accreditation Program
DOL	U.S. Department of Labor
dpm	disintegrations per minute
DU	depleted uranium
EEOICPA	Energy Employees Occupational Illness Compensation Program Act of 2000
ESE	entrance skin exposure
ft	feet
g	gram
GPS	Gas Purification System
GSD	geometric standard deviation
Gy	gray
Hp(10)	personal dose equivalent at 10 millimeters depth in tissue
HEPA	high-efficiency particulate air
HEU	highly enriched uranium
hr	hour
HTO	tritiated water vapor
HVL	half-value layer
ICP-MS	inductively coupled plasma–mass spectrometry
ICRP	International Commission on Radiological Protection
ICT	Insulating Core Transformer
in.	inch
IREP	Interactive RadioEpidemiological Program
keV	kiloelectron-volt, 1,000 electron-volts
kVp	peak kilovoltage
L	liter
LAT	lateral

LLD	lower limit of detection
LLNL	Lawrence Livermore National Laboratory
LSC	liquid scintillation counting or counter
m	meter
mA	beam current
MBA	Mass Balance Area
mCi	millicurie
MDA	minimum detectable amount
MDC	minimum detectable concentration
MDL	minimum detection limit
MeV	megaelectron-volt, 1 million electron-volts
mg	milligram
mGy	milligray
mL	milliliter
mm	millimeter
mm Al	millimeters of aluminum
mR	milliroentgen
mrad	millirad
mrem	millirem
nCi	nanocurie
NIOSH	National Institute for Occupational Safety and Health
NTA	nuclear track emulsion, type A
NVLAP	National Voluntary Laboratory Accreditation Program
ORAU	Oak Ridge Associated Universities
PA	posterior-anterior
pCi	picocurie
PER	program evaluation report
RDC	Radiation Detection Company
RESL	Radiological and Environmental Sciences Laboratory
s	second
SEC	Special Exposure Cohort
SID	source-to-image distance
SNL	Sandia National Laboratories
SNL-CA	SNL Livermore, California, facilities
SNL-NM	SNL Albuquerque, New Mexico, facilities
SOP	Safe Operating Procedure
SRDB Ref ID	Site Research Database Reference Identification (number)
SSD	source-to-skin distance
SWP	Safe Work Permit
T_2	elemental tritium
TBD	technical basis document
TLD	thermoluminescent dosimeter
TMA/EAL	Thermo-Analytical Incorporated/EAL Corporation
TRL	Tritium Research Laboratory
U.S.C.	United States Code
VERS	Vacuum Effluent Recovery System

wk	week
yr	year
µCi	microcurie
µg	microgram
µR	microroentgen
§	section or sections

1.0 INTRODUCTION

Technical basis documents and site profile documents are not official determinations made by the National Institute for Occupational Safety and Health (NIOSH) but are rather general working documents that provide historical background information and guidance to assist in the preparation of dose reconstructions at particular Department of Energy (DOE) or Atomic Weapons Employer (AWE) facilities or categories of DOE or AWE facilities. They will be revised in the event additional relevant information is obtained about the affected DOE or AWE facility(ies). These documents may be used to assist NIOSH staff in the evaluation of Special Exposure Cohort (SEC) petitions and the completion of the individual work required for each dose reconstruction.

In this document the word "facility" is used to refer to an area, building, or group of buildings that served a specific purpose at a DOE or AWE facility. It does not mean nor should it be equated to an "AWE facility" or a "DOE facility." The terms AWE and DOE facility are defined in sections 7384l(5) and (12) of the Energy Employees Occupational Illness Compensation Program Act of 2000 (EEOICPA), respectively. An AWE facility means "a facility, owned by an atomic weapons employer, that is or was used to process or produce, for use by the United States, material that emitted radiation and was used in the production of an atomic weapon, excluding uranium mining or milling." 42 U.S.C. § 7384l(5). On the other hand, a DOE facility is defined 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 [DOE] (except for buildings, structures, premises, grounds, or operations … pertaining to the Naval Nuclear Propulsion Program);" and with regard to which DOE has or had a proprietary interest, or "entered into a contract with an entity to provide management and operation, management and integration, environmental remediation services, construction, or maintenance services." 42 U.S.C. § 7384l(12). The Department of Energy (DOE) determines whether a site meets the statutory definition of an AWE facility and the Department of Labor (DOL) determines if a site is a DOE facility and, if it is, designates it as such.

Accordingly, a Part B claim for benefits must be based on an energy employee's eligible employment and occupational radiation exposure at a DOE or AWE facility during the facility's designated time period and location (i.e., covered employee). After DOL determines that a claim meets the eligibility requirements under EEOICPA, DOL transmits the claim to NIOSH for a dose reconstruction. EEOICPA provides, among other things, guidance on eligible employment and the types of radiation exposure to be included in an individual dose reconstruction. Under EEOICPA, eligible employment at a DOE facility includes individuals who are or were employed by DOE and its predecessor agencies, as well as their contractors and subcontractors at the facility. Unlike the abovementioned statutory provisions on DOE facility definitions that contain specific descriptions or exclusions on facility designation, the statutory provision governing types of exposure to be included in dose reconstructions for DOE covered employees only requires that such exposures be incurred in the performance of duty. As such, NIOSH broadly construes radiation exposures incurred in the performance of duty to include all radiation exposures received as a condition of employment at covered DOE facilities in its dose reconstructions for covered employees. For covered employees at DOE facilities, individual dose reconstructions may also include radiation exposures related to the Naval Nuclear Propulsion Program at DOE facilities, if applicable. No efforts are made to determine the eligibility of any fraction of total measured exposure for inclusion in dose reconstruction.

NIOSH does not consider the following types of exposure as those incurred in the performance of duty as a condition of employment at a DOE facility. Therefore these exposures are not included in dose reconstructions for covered employees (NIOSH 2010):

- Background radiation, including radiation from naturally occurring radon present in conventional structures
- Radiation from X-rays received in the diagnosis of injuries or illnesses or for therapeutic reasons

1.1 PURPOSE

This site profile for the Sandia National Laboratories (SNL) site in Livermore, California (SNL-CA), describes aspects of the SNL-CA site and historical activities and practices pertinent to dose reconstruction under EEOICPA.

1.2 SCOPE

Section 2.0 describes the site and the activities. Section 3.0 addresses the protocol and procedures associated with routine occupational medical X-rays of SNL-CA employees. Estimated occupational intakes from above-background ambient levels of radionuclides in the SNL-CA environment are provided in Section 4.0 along with estimated external ambient dose rates. Sections 5.0 and 6.0 address the technical issues in relation to measurement of internal and external dose, respectively. Attributions and annotations, indicated by bracketed callouts and used to identify the source, justification, or clarification of the associated information, are presented in Section 7.0.

1.3 SPECIAL EXPOSURE COHORT

NIOSH has determined that it is not feasible to reconstruct certain components of internal and external dose from October 1, 1957, through December 31, 1994, due to a lack of sufficient information, which includes biological and workplace monitoring data and radiological source information (Sebelius 2013):

> *All employees of the Department of Energy, its predecessor agencies, and its contractors and subcontractors who worked in any area at Sandia National Laboratories-Livermore in Livermore, California, from October 1, 1957 through December 31, 1994, for a number of work days aggregating at least 250 work days, occurring either solely under this employment, or in combination with work days within the parameters established for one or more other classes of employees in the Special Exposure Cohort.*

NIOSH lacks sufficient information, which includes internal and external personnel monitoring data, process data, and radiological source term information, to allow it to estimate with sufficient accuracy the potential internal and external exposures to radionuclides that include but are not limited to uranium, uranium tritides and hydrides, tritium, and thorium, as well as potential exposures from classified radiological activities to which the class may have been subjected. NIOSH finds that it is likely feasible to reconstruct occupational medical dose for SNL-CA workers with sufficient accuracy through 1989 (NIOSH 2013). Since 1989, medical X-rays have been performed at Lawrence Livermore National Laboratory (LLNL) (ORAUT 2006a).

2.0 SITE DESCRIPTION

2.1 INTRODUCTION

2.1.1 Purpose

This section briefly describes the physical environment of the SNL-CA site and the site activities and processes carried out since its establishment in 1956.

2.1.2 Scope

The types of radioactive materials present on the SNL-CA site, the areas in which exposure to radioactive materials may have occurred, and the emissions of radionuclides to the environment are identified. Access control for radioactive areas is also described.

2.1.3 Background

The information in this introductory section was taken primarily from Ullrich (2003), which was prepared to support DOE's compliance with the National Historic Preservation Act. The SNL-CA site was established in 1956 to provide direct support for LLNL nuclear weapons designs. The primary mission during the Cold War (1956 to 1989) was the design and testing of nonnuclear components of nuclear weapons designed by LLNL. SNL-CA was to engineer, or "weaponize," the nuclear physics packages. Production of parts and final weapons was accomplished at other weapons complex sites.

From 1956 to 1993, SNL-CA was managed and operated by American Telephone and Telegraph. In 1993, the contract was awarded to Martin Marietta Corporation, now known as Lockheed Martin Corporation (DOE 2003). Sandia Corporation, a Lockheed Martin Company, operated SNL-CA and Sandia National Laboratories-New Mexico (SNL-NM) in Albuquerque. In May 2017, the contract was awarded to National Technology and Engineering Solutions of Sandia, a wholly owned subsidiary of Honeywell International.

The SNL-CA site presently consists of approximately 70 buildings and other facilities on 410 acres just across East Avenue from the LLNL in Livermore, California. Figure 2-1 shows the SNL-CA facilities in relation to the boundaries; Figure 2-2 shows the individual buildings/facilities on the site.

The SNL-CA site initially consisted of a long narrow strip of 50 acres stretching south from East Avenue. A personnel building was first completed in September 1957; the rest of the original buildings (warehouse, model shop, environmental test, central steam plant, and office and laboratory building) were completed in 1958. Design support for LLNL was originally provided by a small group of engineers and support staff. At first, 14 SNL-NM employees worked with LLNL in LLNL facilities. In 1957, SNL-CA began using LLNL Site 300 for explosive testing. By 1958, with over 800 employees, SNL-CA worked on the W38 warhead for Titan I and Atlas missiles. Support of LLNL activities expanded to include effects test analyses and telemetry for tests of nuclear weapon designs. As part of the Plowshare Program, which ended in the early 1970s, SNL-CA also moved into evaluation of nuclear detonation in 1959 (Ullrich 2003).

The environmental test building for the new SNL-CA site (completed by the end of 1958) was used for some testing of new designs. During the 1960s, more support facilities were built, including storage and a maintenance shop. Additional test facilities (the centrifuge and Explosive Test Facility) were constructed. In 1970, 86 acres were added to the site, providing an additional buffer area.

Although SNL-CA retains its core mission of nuclear ordnance design and testing, the laboratory moved further into scientific research in the late 1960s, bringing in scientists, mathematicians, and materials specialists to work in applied research. The initial move into research on ^{3}H grew out of its familiarity with, and use of, ^{3}H in components. In 1974, the first structure dedicated to ^{3}H research at SNL-CA, the Tritium Research Laboratory (TRL), was added to the site with completion of the basic laboratory building during the summer of 1975 (Garcia and Gorman 1996). The TRL became operational in late 1978.

Ranging further from weapons engineering, SNL-CA also pursued combustion research and, during the 1973 to 1974 energy crisis, began conducting some research into alternative energy. The expanded purpose of SNL-CA resulted in an increased variety of facilities at the site. In addition to the TRL, a large complex for the Combustion Research Facility was completed in 1980. An additional 24 acres of land were added as a buffer zone on the east side near the TRL in 1979. In 1986, an additional 228 acres were obtained, allowing an alternative exit route from the facility. Finally, in 1998, SNL-CA took part in a small land exchange to create a consistent buffer zone line along the western boundary, in which 2.82 acres were received in exchange for 5.41 acres. This brought the

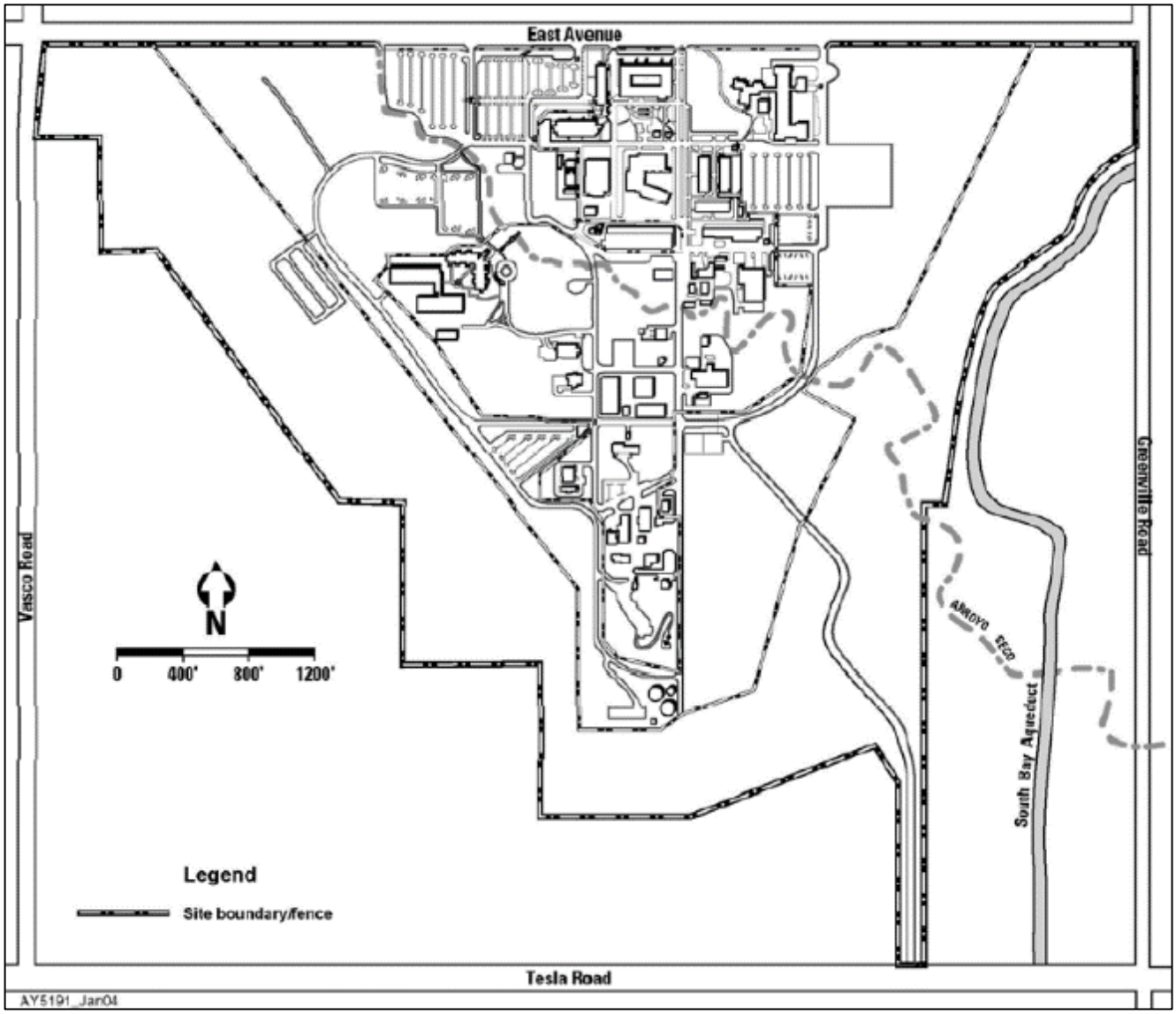


Figure 2-1. Boundaries of SNL-CA property (Larsen 2005).

site's area down to 410 acres where it remains today. In 2004, there were 1,094 employees at the site (Larsen 2005).

2.2 SITE ACTIVITIES

In support of the various missions identified in Section 2.1.3, a number of activities were undertaken at SNL-CA over the years, some of which involved handling and release of radioactive materials. A complete list of buildings along with known information about present and past uses and the presence of radioactive materials is given in Attachment A. A subset of this building list can be alternatively compiled to represent the major process complexes at the SNL-CA site that handled radioactivity in some manner over the years (as shown in Table 2-1) and the predominant radiologically related activities that took place in these complexes.

According to SNL-CA annual environmental reports dating back to 1983, the laboratory typically handled kilogram amounts of depleted uranium (DU), gram amounts of ^{3}H (when the TRL was operational), and only microcurie quantities of other isotopes (SNL 1983). However, the 1992 Environmental Impact Statement for LLNL and SNL-CA noted 100 Ci ^{192}Ir and ^{60}Co radiographic

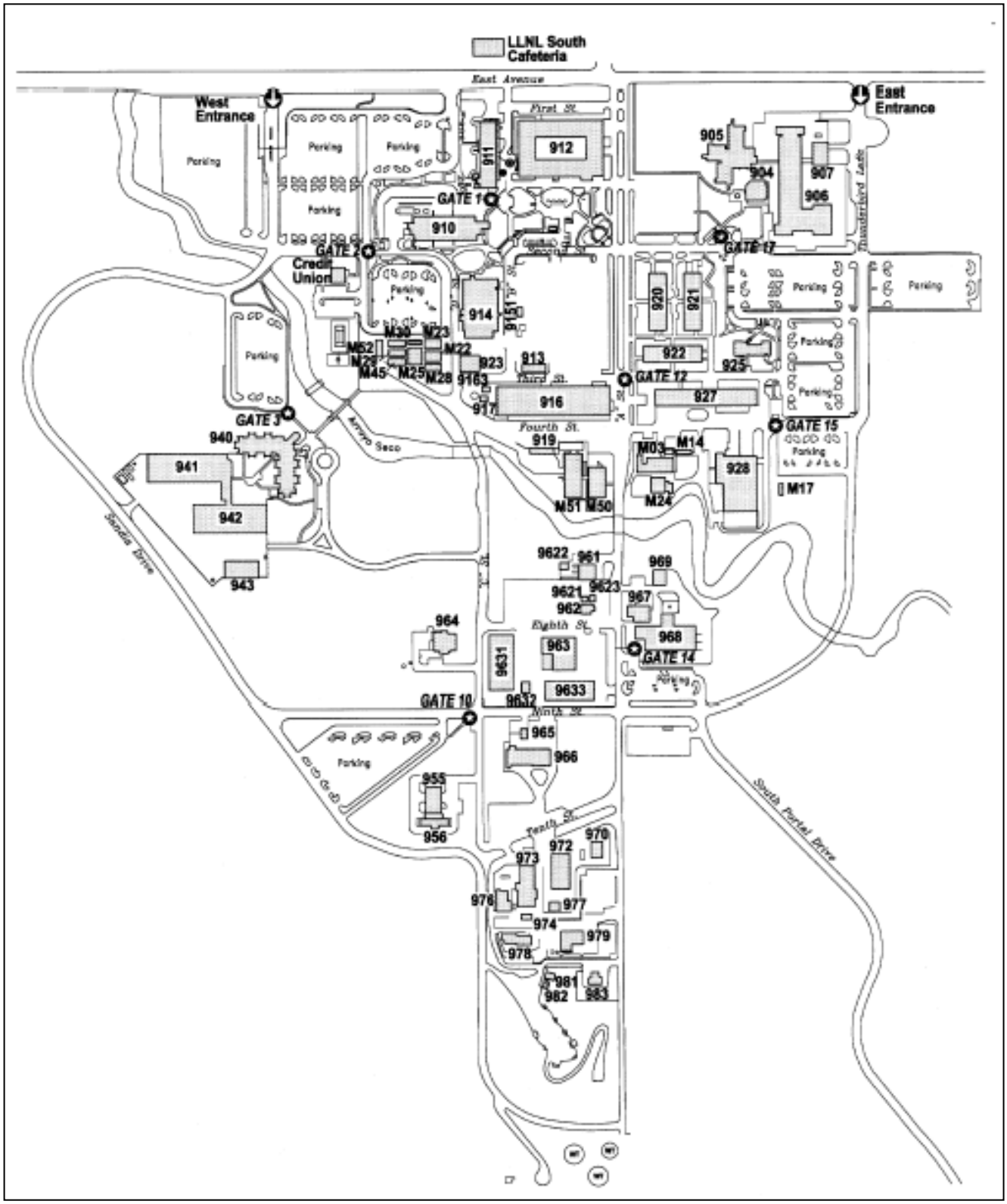


Figure 2-2. Map of SNL-CA facilities (Ullrich 2003).

isotopes and many other smaller sealed sources, with activities ranging from 1 µCi to 500 mCi, stored in a shielded radiography cell (DOE 1992, Volume II).

Table 2-1. Area information and parameters.[a]

Area	Weapons Laboratory Facility Complex
Description	Buildings 910, 912, 913, 914, 916, 918
Period	1958–1998
Activities	Test/repair neutron detectors, wet machining of DU, radiography of weapons components, radiography for materials science studies, H-3 storage studies, ion beam analysis of materials, Radiflo leak tests
Radiation sources	DU, H-3, neutron generator, small accelerators, small sealed sources, small amounts of Kr-85

Area	Radiography
Description	Building 923
Period	Unknown–early 1990s
Activities	Radiography using X-rays, gamma rays, neutrons, alpha and beta particles
Radiation sources	Co-60, Ir-192, Cf-252, X-ray machines

Area	Micro and Nano Technologies Laboratories
Description	Buildings 941, 942, and 943
Period	Unknown–present
Activities	Radiography for materials science studies
Radiation sources	In Building 941 only: X-ray, U-238, and beta sources (sealed)

Area	Former Tritium Research Laboratories (currently the Chemical and Radiological Detection Laboratory)
Description	Buildings 967, 968, and 969
Period	1974–1996
Activities	H-3 research: >0.1 g H-3 handled in glovebox, 0.0005–0.1 g in high velocity air hoods
Radionuclides	H-3, DU (no radionuclides after decommissioning complete in 1996)

Area	Explosives and Environmental Testing Complex
Description	Buildings 955, 956, 966, 972, 974, 976, 977, 978, 979, 981, 983
Period	1958–present
Activities	Environmental testing of mock-up weapons and components
Radionuclides	DU

Area	Storage Facilities
Description	Buildings 921 (became Building 9632 in 1980), 927, 961, 982
Period	Unknown–present
Activities	Storage and packaging of waste materials
Radionuclides	H-3, DU, natural thorium, trace Pu-239 and mixed fission products

a. DU = depleted uranium.

DU is, and has been, largely in the form of alloyed metal components, often encapsulated. Wet machining of uranium metal did occur over the years (Adolphson 1972; SNL 1989; Wallace 1988). Powdered DU sealed in storage containers for ^{3}H-storage studies (as the tritide) has also been present in approximately 1-kg amounts (SNL 1991a). A classified activity involving powdered uranium hydride in gram amounts was conducted in gloveboxes in Buildings 979, 916, and the TRL (ORAUT 2006a). There were some thorium metal parts used on test systems as well (ORAUT 2006a).

Tritium was generally handled in the TRL in the form of a gas, although effluents could be in the form of a gas, liquid, or solid. Mixed solid and liquid tritiated waste was generated, the majority of which was in the form of scintillation cocktails that were shipped off site for incineration in Florida (DOE 1992, Volume II). Details about total quantities of ^{3}H present for each year of operation of the TRL

and pertinent to types of research activities carried out in this facility are described in Section 2.2.1 below.

Most of the remaining radioactive materials were contained in sealed sources. However, a small amount of ^{85}Kr was used in the Radiflo leak detection studies. The period of use of the Radiflo units is not known.

In 1982, the Final Environmental Impact Statement for LLNL and SNL-CA (DOE 1982) indicated that the major activities taking place on the SNL-CA site related to "tritium research; arming, fusing and firing systems; and aerodynamic and structural elements used in U. S. nuclear bombs and warheads." At that time, it was found that operations within most facilities on site had no significant environmental impact and they involved radionuclides in small enough quantities that special containment features and operating procedures were not required to ensure that no radioactivity was released. The only exceptions to this finding of no potential significant impact were the SNL-CA radioactivity storage vaults, one of which was in Building 927, another small vault within the TRL (Building 968), and the TRL itself. The contents of the 927 vault varied according to work needs, but generally included DU-containing mock-ups of weapons and small, sealed radioactive sources not in use. Tritium was not stored in the 927 vault; rather the small quantities on site were kept in the laboratories where they were being used in Building 968 or in the vault in that building. Other than the ^{3}H sources from the vaults in Building 968 (the TRL), experiments were conducted with up to 120 g (1.2×10^{6} Ci) of ^{3}H per experiment in sealed gloveboxes.

In 1992, the *Final Environmental Impact Statement and Environmental Impact Report for Continued Operation of Lawrence Livermore National Laboratory and Sandia National Laboratories* (DOE 1992, Volume II) concluded that the only building for which a potentially significant radiological release could occur under accident conditions would be Building 968, which housed the TRL at that time. This was based on a review of all potential radiological sources and the likelihood that the source could become dispersed into the onsite or offsite environment.

The 2003 *Final Site-Wide Environmental Assessment of the Sandia National Laboratories/California* (DOE 2003) addressed, in part, the potential environmental impact of continuing operations at the SNL-CA. The TRL operations were discontinued in 1996 (including the decontamination activities); therefore, the radiological activities at that time involved radioactive material management of legacy radioactive material inventories and current nuclear material inventories, including radioactive isotopes used in laboratory research and radiation monitoring activities.

A Waste Management Site Plan from 1980 states (Wright 1981a):

> *The radwastes comprise, primarily, tritium and depleted uranium (D-38) but no Transuranics, fission products or induced activity. Now that the Tritium Research Laboratory is operational, tritium contamination will account for more than 50% of the radwaste volume in FY80. Depleted uranium contaminated wastes will account for most of the remainder. D-38 wastes are mostly machine turnings from the Machine Shop in Bldg. 913 and components from the Test Assembly Group also in Bldg. 913. Contaminated paper and machine lubricants make up most of the actual D-38 waste volume. D-38 components may be classified or unclassified.*

This information suggests that activities involving DU and ^{3}H are the only two potentially significant sources of internal exposure to workers based largely on the fact that these are the only two radioactive materials present in significant quantities throughout the history of SNL-CA. External exposures to radiation from radiation-generating devices (small accelerators, radiography sources, neutron generators, X-ray machines) are also of concern. The remainder of this section discusses aspects of the SNL-CA site pertinent to these sources of exposure.

2.2.1 Tritium Research Laboratory

The TRL was designed as a modern research and development facility to provide support to the DOE weapons complex (Garcia and Gorman 1996). The TRL was the first major ^{3}H research and development complex to use secondary containment coupled with a cleanup system as a means to control personnel exposure to levels as low as is reasonably achievable (ALARA) and reduce environmental releases (Garcia and Gorman 1996). The TRL continued to operate until 1993 when all tritium and associated research was transferred to other DOE facilities. The TRL was decontaminated from January 1994 through October 1996 and now houses the Chemical and Radiation Detection Laboratory (CRDL).

Administrative controls limited the amount of tritium in the research laboratory to a maximum of 120 g at any time (excluding the vault) and to a maximum of 300 g at the facility in total at any time (Wall 1981). Table 2-2 lists the historical inventory of elemental tritium (T_2) at TRL (from Garcia and Gorman 1996).

Table 2-2. Historical T_2 inventory at TRL.

Year	Mass (g)	Activity (Bq)
1979	1.06	3.8E+14
1980	15.47	5.5E+15
1981	29.62	1.1E+16
1982	28.55	1.0E+16
1983	27.62	9.8E+15
1984	37.86	1.3E+16
1985	85.49	3.0E+16
1986	107.58	3.8E+16
1987	174.35	6.2E+16
1988	181.59	6.4E+16
1989	148.89	5.3E+16
1990	115.46	4.1E+16
1991	117.85	4.2E+16
1992	131.67	4.7E+16
1993	101.21	3.6E+16
1994	29.43	1.0E+16
1995	9.96	3.5E+15
1996	4.04	1.4E+15
1997	0	0.0E+00

The TRL was divided into nine laboratories, two office areas, a ^{3}H storage room, a control room, a shop, a ^{3}H gas purification equipment room, and eight miscellaneous rooms. The Radioactive Materials Area was separated from the rest of the facility by two sets of double doors. The ventilation system directed airflow from clean areas to areas of increasing contamination potential (Wright 1981a).

Operations in the TRL depended on the types of research but were focused on the physical and chemical characterization of ^{3}H and its compounds, the fabrication of tritium compounds for use as engineering components (Wright 1981a), and examining the behavior of hydrogen isotopes and helium in metals to understand transport and structural properties (Garcia and Gorman 1996). Operations were performed inside sealed gloveboxes for any experiments involving more than 0.1 g of ^{3}H (DOE 1992, Volume II).

Building 968 was not operated as a security exclusion area. Building access was controlled by a sign-in/sign-out procedure until a computer-based security system was put in place, which is known to

have been in place in 1991 (SNL 1991b). Radiological materials were also dispensed through one authorized person and amounts were administratively controlled. The Nuclear Material Management Group had three Mass Balance Areas (MBAs) and a custodian for each area was responsible for issuing nuclear materials to personnel in that MBA. Material was accounted for to the nearest 0.01 g, with amounts equal to or greater than 0.005 g rounded to the nearest 0.01 g.

Two central decontamination systems were used: (1) Gas Purification System (GPS) and (2) Vacuum Effluent Recovery System (VERS). The GPS was used to remove tritium, tritiated water, and tritiated hydrocarbons from the sealed glovebox atmosphere in the event of either a significant release or a slow buildup of background contamination. The VERS was used to remove tritium, tritiated water vapor (HTO), and tritiated hydrocarbons from the glovebox pressure control system and the gases exhausted from all of the vacuum pumps in the laboratory before venting to the stack.

2.2.2 Depleted Uranium Machining

Machine shops in Buildings 913, 914, and in an annex of Building 918 were used for machining of DU fairly infrequently at SNL-CA. A 1972 memorandum from Adolphson (1972) indicates that "machining of uranium alloy test specimens" began in 1971. No machining has been done since 1998, when Building 913 was decommissioned. According to the Health Physicist at SNL-CA, this machining was done as a wet process with the exception of one accident he was aware of in which dry cutting occurred (ORAUT 2006a). The 1989 Safe Operating Procedure (SOP) for machining of uranium metal (SNL 1989) dictated that all machining operations were to be performed wet and that dry operations were prohibited. According to a 1985 DOE Headquarters appraisal of SNL-CA and response to findings (Wallace 1988), uranium machining occurred approximately once or twice a quarter. The appraisal and response report also indicates that the Hazards Control Division at SNL-CA, as of 1987, had 16 years of air sampling data for this procedure, which "demonstrate that airborne contamination is not a problem during typical machining operations."

2.2.3 Radiography, Accelerators, and Neutron Generators

Until the early 1990s, the Radiography Facility was a 3,880-ft^2 building (Building 923) that included X-ray machines, a gamma-ray source, neutron sources, and many alpha and beta sources (DOE 1992, Volume II). The radiation sources were primarily used for the radioscopy and electron imaging of weapon and nonweapon components. The radiation sources included the radiation-producing machines with energies up to 420,000 volts, the 100 Ci ^{192}Ir and ^{60}Co radiographic isotopes, the sealed ^{252}Cf spontaneous fission neutron source inside a massive neutron source shield, and many other smaller sealed neutron, alpha, beta, and gamma-ray isotope sources of low activity (1 µCi to 500 mCi), which were stored in a shielded radiography cell. The building contained four shielded radiography cells. The sources were used infrequently for material characterization studies involving radiation transmission gauging, backscatter measurements, X-ray fluorescence studies, and neutron activation analysis (DOE 1992, Volume II).

X-ray diffraction equipment is reported as being present in Building 913, Room 115, as early as 1965 (SNL 1964). An incident that occurred with a diffractometer (see Section 2.3.1) was reported to have occurred in Building 913, Room 113 in 1979 (Lovell 1980). Radiography is currently conducted in Building 941, part of the Micro and Nanotechnologies Laboratory (DOE 2003).

Two small accelerators have been and remain in Building 916 (DOE 1992, Volume II; DOE 2003). These include a 1-MeV Tandem accelerator and a 700-/200-keV positive ion accelerator (Morse 1983; SNL 1991c; ORAUT 2006a).

There are neutron generators used in the design, assembly, testing, calibration, and repair of neutron detectors in Building 910 (SNL 1990). Neutron generator tests are also conducted in Building 974 (Attachment A).

2.3 SITE PROCESSES

2.3.1 Incidents

According to Garcia and Gorman (1996), a few incidents occurred in relation to the TRL that could have led to ^{3}H exposures in excess of routine operations. Other sources (Lovell 1980; SNL 1960–1983) listed excess exposure to ionizing radiation, but only one was attributable to a work-related exposure. These incidents are listed below.

Personnel Exposure to Ionizing Radiation, December 1979
[Redacted]. This resulted in a dose assignment of 26 to 34 rem to the basal cell layer of a skin area (less than 400 cm^2) of the chest and arm (Lovell 1980).

A similar event was reported through worker interviews to have occurred in 1978 involving the same equipment operated under similar circumstances. NIOSH has determined that this event was of less severity than that in 1979 (NIOSH 2007a). The dose evaluation described for the 1979 event as described above should be used for the earlier event (Lovell 1980).

Personnel Exposure and Tritium Release, July 1984
During disassembly of an engineering experiment in [redacted], an environmental release of approximately 2.5 Ci of [redacted] occurred. [Redacted] employees received doses ranging from a high of 1,650 mrem down to 2 mrem.

Tritium Release, January 1986
A weld crack in a storage container caused a leak and release in the Decontamination Laboratory 115A causing an environmental release of 200 Ci of HTO. There were no resulting personnel exposures.

Personnel Exposure and Tritium Release, August 1987
An 1,100-Ci environmental release occurred when an [redacted] disassembled a vessel [redacted] in [redacted]. This release of T_2 caused a building evacuation, and an [redacted] received a dose of 15 mrem.

Tritium Release, October 1988
An environmental release occurred during a GPS Regeneration operation in Laboratory 115A. The release was estimated at 124 Ci of HTO, and no personnel exposure was involved.

Personnel Exposure and Tritium Release, March 1989
A personnel exposure of about 180 mrem occurred during VERS pump maintenance operations in Laboratory 120. An environmental release of approximately 11.5 Ci of HTO occurred. Subsequent operation required the flushing of pumps before pump maintenance operations.

Personnel Exposure and Tritium Release, October 1993
[Redacted] personnel received doses from 2 to 5 mrem when a [redacted] failed and caused a tritium release in [redacted]. An environmental release of 2 Ci HTO was reported by Garcia and Gorman (1996), but it was also reported as a 30-Ci stack release by Garcia (1994a). The personnel doses came from both cleanup and [redacted] replacement operations.

2.3.2 Effluents

The only radionuclides released due to normal operations from SNL-CA have been small amounts of tritium and trace amounts of DU (SNL 1982, 1983, 1984; Devlin 1986 to 1988; Siegfriedt 1989; Brekke 1990, 1991; Brekke and Holland 1992 to 1995; Holland and Brekke 1996; Holland 1997 to 2002; Larsen 2003 to 2005). The DU effluents are reported to be less than 10 µCi ([3.7×10^{-5} Bq] for both liquid and airborne effluents collectively [SNL 1982, 1983, 1984; Devlin 1986]). In 1990, DOE (1990) reported that emissions of radioactive particulates from SNL-CA activities that potentially generate such particulates were controlled with high-efficiency particulate air (HEPA) filters. A total of 33 HEPA filters in four buildings (913, 916, 961, and 979) were in use at that time. Tritium from the TRL has been the only airborne effluent routinely reported, and has often been declared to be the only detectable effluent (Devlin 1986 to 1988; Siegfriedt 1989; Brekke 1990, 1991; Brekke and Holland 1992 to 1995; Holland and Brekke 1996; Holland 1997). Monitoring of tritium effluents from the TRL ceased in 1996 after the facility was transitioned for other uses (Holland 1998).

Table 2-3 lists the measured effluents during the operational and decontamination periods of the TRL (Garcia and Gorman 1996). These quantities include the incidental releases noted in Section 2.3.1 above.

Table 2-3. Effluents of ^{3}H to air and sewer during operations and cleanup of TRL.

Year	Total tritium in stack discharges to air (Bq)	Estimated HTO to air (Bq)	Total tritium (as HTO) in wastewater discharges to sewer (Bq)
1979	2.2E+11	Not estimated	1.5E+08
1980	9.3E+11	Not estimated	1.5E+08
1981	1.6E+12	Not estimated	5.7E+09
1982	7.5E+12	Not estimated	1.1E+10
1983	3.5E+12	2.7E+12	1.4E+10
1984	6.1E+12	5.4E+12	1.4E+10
1985	1.9E+13	1.4E+13	7.4E+10
1986	2.7E+13	2.3E+13	9.3E+08
1987	6.8E+13	2.1E+13	8.7E+09
1988	5.8E+13	3.8E+13	1.7E+10
1989	3.1E+13	2.4E+13	1.1E+10
1990	1.1E+13	9.0E+12	7.4E+09
1991	1.7E+13	1.3E+13	4.6E+09
1992	9.8E+12	5.0E+12	2.3E+09
1993	7.0E+12	4.9E+12	2.5E+09
1994	3.5E+12	3.4E+12	2.2E+09
1995	2.7E+12	2.7E+12	8.9E+08
1996	2.9E+09	Not estimated	0.0E+00

2.4 RADIOLOGICAL PROTECTION AND ACCESS CONTROL

Badging and bioassay programs were carried out throughout the history of operations at SNL-CA to provide information on exposure to workers. This information was used to limit annual exposures to workers to within exposure guidelines set forth by the U.S. Atomic Energy Commission (AEC), U.S. Energy Research and Development Administration, and DOE criteria (Kingsley 1968; Nester 1994; SNL undated a). When workers traveled to other locations, such as across the street to the LLNL site, the LLNL Site 300, or other non-SNL-operated sites, the host sites were to be requested to report exposures at those locations to the appropriate staff at SNL-CA or SNL-NM (SNL undated b). A response to the DOE site appraisal finding related to offsite dosimeters indicated that SNL-CA directed employees to “request internal and/or dosimetry, workplace monitoring, etc., if they must enter radiation controlled areas at the visited facility” in 1985 (Wallace 1988).

Dosimetry records for SNL-CA employees were transferred to the SNL-NM site in the late 1980s to the early 1990s (Hallman 1989, 1990; Perez-Romo 1994). A 1994 memorandum indicated that dosimetry data on computer tapes from Reynolds Electric and Engineering Company (the contractor providing base support at the Tonopah Test Range where SNL-Tonopah employees worked) were also sent for storage at SNL-NM (Perez-Romo 1994). It does not appear that the records from before 1989 for SNL-CA were incorporated into the current database at SNL-NM for SNL employees. Dosimetry data for the period from 1973 to 1987 was recently recovered from SNL-NM, and data for 1988 was recovered from SNL-CA. Cumulative summary data for the period before 1973 has also been recovered from SNL-CA. However, annual data for all years before 1973 is currently being sought.

All SNL-CA workers were required to wear dosimetry badges between 1959 and 1969 according to a collection of annual Summary of Whole-Body Radiation Exposures to ionizing radiation reports (SNL 1958–1978). In 1958, the radiation exposure summary report indicates that 41 employees (of 537) were not monitored. However, a 1960 internal memorandum indicates that all employees were monitored from the time of establishment of the Sandia Livermore Corporation (SNL 1958–1961). It was noted in 1984 that Building 923 and Room 100 of Building 916 had sources and/or equipment capable of producing radiation levels that could exceed 500 mrem/yr (which was 10% of the Radiation Protection Standards for workers at that time) (Lovell 1984a,b). Lovell (1984a,b) stated that radiation dosimeters would be required for access to these buildings during radiographic procedures and during accelerator operations. In 1965, DeSelm (1965) wrote a memorandum indicating that Buildings 911 (Medical), 913, 914, 916, 921, 9143, and Areas 8 and 9 could produce levels exceeding the AEC Manual Chapter 0524 (AEC 1963) criteria of 6 mR/hr for radiation exposure to the whole body or critical organs for wearing dosimeters.

Other than requiring dosimeters for access to certain facilities at SNL-CA, there are other forms of access control in place. The 700-/200-keV accelerator (Room 104, Building 916) and 1-MeV tandem accelerator were fitted with interlocks to prevent entry during operation (SNL 1991c; Morse 1983). Access was also restricted to the machine shop (Room 119) in Building 913 during uranium machining operations by roping off the area and having supervisors present during all such operations (SNL 1989). For the TRL (Building 968), building access was controlled by a sign-in/sign-out procedure until a computer-based security system was put in place, as noted in Section 2.2.2.

3.0 OCCUPATIONAL MEDICAL DOSE

As part of the requirements for employment at SNL-CA starting in 1956, some employees received periodic physical examinations. These could include annual radiographic examinations of the chest, as well as lumbar spine X-rays and lateral (LAT) chest X-rays at hire. Because these examinations were required for employment, the *External Dose Reconstruction Implementation Guideline* (NIOSH 2007b) and 42 CFR Part 82 require the X-ray doses to be part of the occupational radiation exposure. This section discusses medical screening X-rays required as a condition of employment; it does not include diagnostic and therapeutic exposures that were not required for employment.

The following sections describe the methodology used to estimate absorbed dose from X-ray exposure for SNL-CA workers. Section 3.1 describes X-ray examination frequency at SNL-CA as reconstructed from claimant files. Section 3.2 provides information on equipment and techniques used at SNL-CA, including assumptions necessitated by lack of protocol, measurement, or records data. Section 3.3 provides organ dose estimates by calendar year and type of X-ray. Section 3.4 documents uncertainties.

3.1 EXAMINATION FREQUENCY

Protocol for the frequency and type of X-ray examinations for SNL-CA workers from 1956 through the present time has not been found. A protocol for the frequency of chest X-ray examinations as a function of job category has also not been found and equipment type is not known. However, claimant files available at this time generally indicate that a single posterior-anterior (PA) chest X-ray examination was performed at hire, annually, and possibly at termination from 1956 through the 1980s. Those records also show that anterior-posterior (AP) and LAT lumbar spine X-rays were at least sometimes performed at hire as late as 1971. LAT chest X-rays were rarely taken; only two files (of over 50 files available at the time) indicate that LAT chest X-rays were taken at hire. LAT chest X-rays should not be included in the default estimates for SNL-CA employees unless it is noted in their medical files that they were taken.

According to the health physics department, worker X-rays ceased in the 1980s, but no specific date is known. The X-ray machine equipment was removed from the site in approximately 1990 (ORAUT 2006a). The clinic at LLNL has provided X-ray services for SNL-CA since 1990 (ORAUT 2006a). No evidence of the use of photofluorography has been found. It is recommended that biennial chest X-rays be assumed for all employees after 1989 (ORAUT 2010a).

3.2 EQUIPMENT AND TECHNIQUES

The analysis assumed that radiological practices followed standards of medical practice to minimize dose to the worker; however, the type of equipment, technique factors, and some machine calibrations are not known. Medical records did record the beam current (mA), peak kilovoltage (kVp), and distance (presumably from machine to image) for PA chest examinations and occasionally for lumbar spine X-rays. The notation of mA in many of the records is likely the exposure (mAs), as the setting recorded in claim files (5 mA) is too low to have produced chest radiographs [1]. Additionally, the distance is assumed to be the source-to-image distance (SID) as it does not vary in the worker files reviewed (it is consistently 72 inches). However, exposure time, filtration, and entrance skin exposure (ESE) were not noted, nor was the use of screens or grids if applicable. A medical X-ray unit was present on the site; personnel report that the X-ray machine was removed in about 1990 and was not replaced. In the 1950s, the preemployment set of X-rays may have been performed at SNL-NM or off the site in California.

This section provides organ dose estimates from occupational X-ray chest examinations administered at SNL-CA from 1956 through 1970, 1971 to 1985, and 1986 to present using calculated site-specific estimates with input from ORAUT-OTIB-0006, *Dose Reconstruction from Occupational Medical X-Ray Procedures* (ORAUT 2019a). For the years through 1970, the default values from ORAUT-OTIB-0006 assume minimal beam collimation and a half-value layer (HVL) of 2.5 mm Al. For 1971 to 1985, the default values assume that the beams were collimated and the HVL was 2.5 mm Al. For 1986 and after, the default values assume collimation and an HVL of 4.0 mm Al. These HVLs were used in the site-specific calculations as site-specific information was not available.

The period for lumbar spine examinations is 1956 through 1971.

For all periods the analysis should assume, as a default, that a single PA chest X-ray occurred at hire, at each annual physical examination, and at termination of employment, as evidenced by available medical records. AP and LAT lumbar spine X-rays were taken once, at hire, for the years 1956 to 1971 [2]. Most workers are assumed to have received these X-rays. LAT chest X-rays were rarely taken, but have been included here for those energy employees with LAT chest X-rays (taken at hire or at a regular physical examination) noted in their medical files (two claim files with this X-ray view have been found). Dose reconstructors should assign dose from the X-ray procedures listed on the preemployment X-ray record form. If the claim file is missing the preemployment X-ray record, the

dose reconstructor should assign dose from a PA chest and AP and LAT lumbar spine as the default for the preemployment X-rays.

Efforts will continue to find related SNL-CA X-ray protocol information. Until that is found, information from claim files related to SNL-CA have been reviewed and notations regarding machine settings (specifically mAs, kVp, and SID) have been used to calculate site-specific estimates of dose received from occupationally required X-ray examinations. The X-ray machine has been assumed to be single phase [3].

3.3 ORGAN DOSE ESTIMATES

This section discusses organ dose estimates. Section 3.3.1 describes the methodology used to estimate these doses and Section 3.3.2 discusses results.

3.3.1 Parameters and Estimation Method

International Commission on Radiological Protection (ICRP) Publication 34 guidance uses the following parameters to estimate air kerma and absorbed dose (ICRP 1982):

- Source to image distance (SID) in centimeters (cm),
- Total filtration (millimeters of aluminum, mm Al),
- Estimate of tissue thickness (AP and LAT), and
- Machine settings (mA, exposure time in seconds, kVp, film size, and machine type).

If measured air kerma are available, they should be used. For SNL-CA, air kerma was estimated from Figure 3-1 assuming a single-phase machine was used at SNL-CA. Assumptions (from medical records within claim files) were used to estimate air kerma for chest X-rays for 1956 to 1970, 1971 to 1985, and 1986 to 1989, after which time X-rays for SNL-CA were performed at LLNL. For the first two periods, 80 kVp, 5 mAs, a total filtration of 2.5 mm Al, and a source-to-skin distance (SSD) of 154 cm results in an air kerma estimate of 0.06 mGy per mAs at 1 m. Total filtration of 2.5 mm Al is a reasonable estimate for those periods (ORAUT 2019a). The entrance kerma is then calculated to be 0.13 mGy, as shown in Table 3-1. The LAT chest entrance kerma is 2.5 times the PA chest entrance kerma (ORAUT 2019a).

For chest X-rays in 1986 and after, 110 kVp, 300 mA and 1/30-s exposure time, and SID of 183 cm (from claim files), with a total filtration estimate of 2.5 mm Al and HVL of 4.0 (ORAUT 2019a) result in an estimated air kerma of 0.126 mGy/mAs and calculated entrance kerma of 0.53 mGy for PA chest X-rays (Table 3-1). The LAT chest X-ray entrance kerma is 2.5 times the PA chest entrance kerma (ORAUT 2019a).

For lumbar spine X-rays (1956 to 1971), an applied kilovoltage of 75 kVp and beam current of 75 mAs were assumed for AP lumbar spine X-rays and 85 kVp and 150 mAs for LAT lumbar spine X-rays based on information in claim files. A total filtration of 2.5 mm Al and HVL of 2.5 mm Al were assumed (ORAUT 2019a), resulting in an estimated air kerma of 0.05 mGy/mAs for AP lumbar spine X-rays and 0.070 mGy/mAs for LAT lumbar spine X-rays. SSDs of 63 cm for AP and 52 cm for LAT X-rays were used, resulting in entrance kerma of 9.45 mGy and 38.8 mGy for AP and LAT X-rays, respectively.

Entrance kerma for PA and LAT chest X-rays and for AP and LAT lumbar spine X-rays are presented in Table 3-1. Dose conversion factors (DCFs) are listed in Table 3-2.

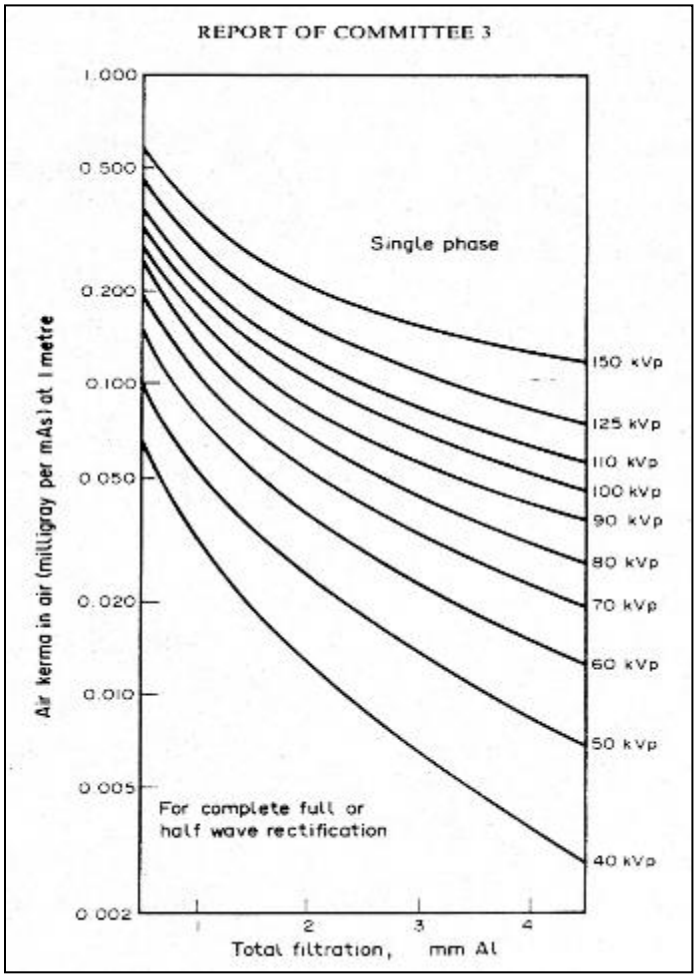


Figure 3-1. Kerma in air at 1 m from X-ray source as a function of total filtration for various values of tube potential (ICRP 1982).

Table 3-1. Entrance kerma by procedure and period.

Period	PA chest entrance kerma (cGy)	LAT chest entrance kerma (cGy)	AP lumbar spine entrance kerma (cGy)	LAT lumbar spine entrance kerma (cGy)
1956–1970 chest	0.013[a]	0.033	Not applicable	Not applicable
1956–1971 lumbar spine	Not applicable	Not applicable	0.945[b]	3.88[c]
1971–1985[a] chest	0.013	0.033	Not applicable	Not applicable
1986–1989[d,e] chest	0.053	0.133	Not applicable	Not applicable

a. Based on 80 kVp and 5 mAs, as observed in SNL-CA claim files and 2.5 mm Al total filtration (ORAUT 2019a). LAT chest entrance kerma is 2.5 times PA chest entrance kerma. PA entrance kerma = (0.06 mGy/mAs) × (5 mAs) × $(100/154\ cm)^2$ = 0.13 mGy.

b. Assumes 75 kVp and 75 mAs, as observed in SNL-CA claim files, and total filtration of 2.5 mm Al (ORAUT 2019a). Entrance kerma = (0.05 mGy/mAs) × (75 mAs) × $(100/63\ cm)^2$ = 9.45 mGy.

c. Assumes 85 kVp and 150 mAs, as observed in SNL-CA claim files, and total filtration of 2.5 mm Al (ORAUT 2019a). Entrance kerma = (0.070 mGy/mAs) × (150 mAs) × $(100/52\ cm)^2$ = 38.8 mGy.

d. Based on 110 kVp, 300 mA and 1/30-s exposure time (noted in one claim file), and total filtration of 2.5 mm Al (ORAUT 2019a). LAT chest entrance kerma is 2.5 times PA chest entrance kerma. PA entrance kerma = (0.126 mGy/mAs) × (10 mAs) × $(100/154\ cm)^2$ = 0.53 mGy.

e. Medical procedures were performed at LLNL after 1989 (ORAUT 2006a). Information post-1989 is found in ORAUT (2010a).

Table 3-2. DCFs (mGy per mGy air kerma); absorbed dose (1 mGy) for organs at various Al HVL for radiography (ORAUT 2019a; ICRP 1982), Appendix 1, Tables A.2–A.8).[a,b,c]

Organ	Lumbar spine DCFs 1956–1971 (2.5-mm Al HVL) LAT	Lumbar spine DCFs 1956–1971 (2.5-mm Al HVL) AP	Chest DCFs 1956–1970 (2.5-mm Al HVL) LAT	Chest DCFs 1956–1970 (2.5-mm Al HVL) PA	Chest DCFs 1971–1985 (2.5-mm Al HVL) LAT	Chest DCFs 1971–1985 (2.5-mm Al HVL) PA	Chest DCFs 1986–1989 (4.0-mm Al HVL) LAT	Chest PA DCFs 1986–1989 (4.0-mm Al HVL) PA
Thyroid	1.00E−05	3.00E−04	1.37E−01	1.74E−01[d]	1.15E−01	3.20E−02	1.64E−01	7.80E−02
Eye/brain	1.00E−05	3.00E−04	1.37E−01	3.20E−02	1.15E−01	3.20E−02	1.64E−01	7.80E−02
Ovaries	Measured[e]	Measured[e]	Measured[e]	Measured[e]	6.00E−04	1.00E−03	2.50E−03	5.20E−03
Liver/ gall bladder/ spleen	Measured[e]	Measured[e]	2.20E−01	4.51E−01	2.20E−01	4.51E−01	3.51E−01	6.74E−01
Urinary bladder	Measured[e]	Measured[e]	Measured[e]	N/A	6.00E−04	1.00E−03	2.50E−03	5.20E−03
Colon/rectum	Measured[e]	Measured[e]	Measured[e]	N/A	6.00E−04	1.00E−03	2.50E−03	5.20E−03
Testes	Measured[e]	Measured[e]	Measured[e]	Measured[e]	1.00E−04	1.00E−05	1.00E−04	1.00E−05
Lungs (male)	1.40E−02	7.90E−02	1.93E−01	4.19E−01	1.93E−01	4.19E−01	3.13E−01	6.28E−01
Lungs (female)	1.40E−02	7.90E−02	2.20E−01	4.51E−01	2.20E−01	4.51E−01	3.51E−01	6.74E−01
Thymus[f]	1.40E−02	7.90E−02	2.20E−01	4.51E−01	2.20E−01	4.51E−01	3.51E−01	6.74E−01
Esophagus[f]	1.40E−02	7.90E−02	2.20E−01	4.51E−01	2.20E−01	4.51E−01	3.51E−01	6.74E−01
Stomach[f]	Measured[e]	Measured[e]	2.20E−01	4.51E−01	2.20E−01	4.51E−01	3.51E−01	6.74E−01
Bone surfaces[f]	Measured[e]	Measured[e]	2.20E−01	4.51E−01	2.20E−01	4.51E−01	3.51E−01	6.74E−01
Remainder[f]	Measured[e]	Measured[e]	2.20E−01	4.51E−01	2.20E−01	4.51E−01	3.51E−01	6.74E−01
Female breast	1.30E−02[g]	2.50E−02[g]	2.55E−01	4.90E−02	2.55E−01	4.90E−02	3.43E−01	1.16E−01
Uterus	3.10E−02	2.87E−01	Measured[e]	Measured[e]	6.00E−04	1.30E−03	2.10E−03	5.20E−03
Bone marrow (male)	2.20E−02	3.70E−02	3.70E−02	9.20E−02	3.70E−02	9.20E−02	7.60E−02	1.78E−01
Bone marrow (female)	2.20E−02	3.70E−02	2.90E−02	8.60E−02	2.90E−02	8.60E−02	5.90E−02	1.72E−01
Skin[h]	1.355E+00	1.355E+00	1.35E+00	1.355E+00	1.35E+00	1.355E+00	1.42E+00	1.42E+00

a. DCFs for lumbar spine are from ICRP (1982, Appendix 1, Tables A.2–A.8) and DCFs for chest are from ORAUT (2019a).
b. N/A = not applicable.
c. Medical procedures were performed at LLNL after 1989 (ORAUT 2006a). Information post-1989 is found in ORAUT (2010a).
d. Per ORAUT (2019a), DCF for AP cervical spine corrected for depth by 0.2.
e. Organ dose values for the testes and ovaries for lumbar spine reflect actual measurements reported in Lincoln and Gupton (1958).
f. Using analogues listed in Table 3-4.
g. DCFs for lumbar spine examination not given in ICRP (1982). Values for the respective upper gastrointestinal examinations were used instead.
h. Backscatter factor from NCRP (1997, Table B-8).

The ICRP tables used to estimate absorbed dose (ICRP 1982) do not include all the organs included in the Interactive RadioEpidemiological Program (IREP). For organs in IREP but not identified in the ICRP tables, the dose conversion coefficient that is anatomically closest to the IREP-specified organs can usually 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 is used. This approach should be either favorable to the claimant or neutral. Table 3-3 lists analogues for IREP organs from ORAUT (2019a).

Table 3-3. Organs without ICRP Publication 34 DCFs and their substitutes.[a]

External organ	ICRP 34 substitute DCF[b]
Thymus, esophagus	Lung
Stomach, bone surface, liver/gall bladder/spleen, small intestine, remainder	Lung[c] or ovary
Urinary bladder, colon/rectum	Ovary
Eye/brain	Thyroid

a. Applies to most properly collimated radiographic procedures.
b. Source: ORAUT (2019a, Table 5-1).
c. The ovary is used as the substitute DCF for these organs for the lumbar spine.

3.3.2 Organ Dose Estimates

Table 3-4 lists calculated organ dose estimates from PA and LAT chest X-ray examinations for each period (through 1970, 1971 to 1985, and 1986 to 1989). LAT chest X-rays were, for the most part, discontinued after 1970; however records for LAT chest X-rays have been discovered for some claims after that time, and should be included. The estimates for exposure from chest X-rays for these periods have been calculated using information taken from claim files in conjunction with assumptions from ORAUT (2019a). Chest X-rays after 1989 were performed at LLNL (ORAUT 2006a).

Table 3-5 presents skin doses from PA and LAT chest X-rays that should be used for each chest X-ray period. These X-rays were often taken at hire.

Table 3-6 presents organ doses from AP and LAT lumbar spine X-rays that should be used for years 1956 to 1971. These X-rays were often taken at hire. Table 3-7 provides skin doses for lumbar spine X-rays during this period. AP skin doses to the hands and forearms are reduced for 1971, based on guidance in ORAUT (2019a).

The B-lymphocyte cells are the tissue at risk for chronic lymphocytic leukemia. The dose equivalent to the B-lymphocytes was determined using the method in ORAUT-OTIB-0082, *Dose Reconstruction Method for Chronic Lymphocytic Leukemia* (ORAUT 2012a), site-specific information, and ICRP Publication 34 DCFs (ICRP 1982). The dose distributions and corresponding statistical parameters for the dose to the B-lymphocytes for each projection and period are listed in Table 3-8.

3.4 UNCERTAINTIES

As stated in the International Vocabulary of Metrology (JCGM 2008), “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 implies knowledge of what the correct or actual value is, which is of course not known. Therefore, the more appropriate factor is uncertainty, which is expressed in terms of a coverage probability (e.g., a 99% coverage probability indicates that the correct or true value, although not actually known, has a 99% probability of falling within the cited range). Uncertainty includes both precision and adjustments for bias.

Table 3-4. Organ dose estimates for chest X-rays (rem).

Organ	1956–1970 estimated dose[a,b,c] HVL = 2.5 mm Al (uncollimated) LAT	1956–1970 estimated dose[a,b,c] HVL = 2.5 mm Al (uncollimated) PA	1971–1985 estimated dose[a,b,c] HVL = 2.5 mm Al (collimated) LAT	1971–1985 estimated dose[a,b,c] HVL = 2.5 mm Al (collimated) PA	1986–1989 estimated dose[a,b,f] HVL = 4.0 mm Al (collimated) LAT	1986–1989 estimated dose[a,b,f] HVL = 4.0 mm Al (collimated) PA
Thyroid	4.52E−03	2.26E−03	3.80E−03	4.16E−04	2.18E−02	3.35E−03
Eye/brain	4.52E−03	4.16E−04	3.80E−03	4.16E−04	2.18E−02	3.35E−03
Ovaries	1.30E−02	2.50E−02	1.98E−05	1.30E−05	3.33E−04	2.24E−04
Liver/gall bladder/ spleen	7.26E−03	5.86E−03	7.26E−03	5.86E−03	4.67E−02	2.90E−02
Urinary bladder	1.30E−02	2.50E−02	1.98E−05	1.30E−05	3.33E−04	2.24E−04
Colon/rectum	1.30E−02	2.50E−02	1.98E−05	1.30E−05	3.33E−04	2.24E−04
Testes	1.30E−02	5.00E−03	3.30E−06	1.30E−07	1.33E−05	4.30E−07
Lungs	7.26E−03	5.86E−03	7.26E−03	5.86E−03	4.67E−02	2.90E−02
Thymus	7.26E−03	5.86E−03	7.26E−03	5.86E−03	4.67E−02	2.90E−02
Esophagus	7.26E−03	5.86E−03	7.26E−03	5.86E−03	4.67E−02	2.90E−02
Stomach	7.26E−03	5.86E−03	7.26E−03	5.86E−03	4.67E−02	2.90E−02
Bone surfaces	7.26E−03	5.86E−03	7.26E−03	5.86E−03	4.67E−02	2.90E−02
Remainder	7.26E−03	5.86E−03	7.26E−03	5.86E−03	4.67E−02	2.90E−02
Female breast	8.42E−03	6.37E−04	8.42E−03	6.37E−04	4.56E−02	4.99E−03
Uterus	1.30E−02	2.50E−02	1.98E−05	1.69E−05	2.79E−04	2.24E−04
Bone marrow	1.22E−03	1.20E−03	1.22E−03	1.20E−03	1.01E−02	7.65E−03
Skin[d,e]	4.46E−02	1.76E−02	4.46E−02	1.76E−02	1.89E−01	6.11E−02

a. SID = 183 cm.
b. Image receptor size 35.6 cm by 43.2 cm.
c. Modified from Webster and Merrill (1957) as presented in ORAUT (2019a).
d. Calculated using backscatter factor of 1.35 from NCRP (1997, Table B-3) for skin dose estimates through 1985; consistent with ORAUT (2019a).
e. Calculated using backscatter factor of 1.42 from NCRP (1997, Table B-3) for skin dose estimates after 1985; consistent with ORAUT (2019a).
f. Procedures after 1989 were performed at LLNL (ORAUT 2006a); doses are as found in ORAUT (2010a).

Table 3-5. Skin area dose estimates from chest X-rays (rem).[a]

Skin area	1956–1970 LAT	1956–1970 PA	1971–1985 LAT	1971–1985 PA	1986–1989[b] LAT	1986–1989[b] PA
R front shoulder	4.46E−02	3.84E−04	4.46E−02	3.84E−04	1.89E−01	2.08E−03
R back shoulder	4.46E−02	1.76E−02	4.46E−02	1.76E−02	1.89E−01	6.11E−02
L front shoulder	1.96E−04	3.84E−04	1.96E−04	3.84E−04	1.41E−03	2.08E−03
L back shoulder	1.96E−04	1.76E−02	1.96E−04	1.76E−02	1.41E−03	6.11E−02
R upper arm to elbow	4.46E−02	1.76E−02	4.46E−02	1.76E−03	1.89E−01	6.11E−03
L upper arm to elbow	4.46E−02	1.76E−02	1.96E−04	1.76E−03	1.41E−03	6.11E−03
L hand	4.46E−03	1.76E−02	4.46E−03	1.76E−03	1.89E−02	6.11E−03

Skin area	1956–1970 LAT	1956–1970 PA	1971–1985 LAT	1971–1985 PA	1986–1989[b] LAT	1986–1989[b] PA
R hand	4.46E−03	1.76E−02	4.46E−03	1.76E−03	1.89E−02	6.11E−03
L elbow, forearm, wrist	4.46E−03	1.76E−02	4.46E−03	1.76E−03	1.89E−02	6.11E−03
R elbow, forearm, wrist	4.46E−03	1.76E−02	4.46E−03	1.76E−03	1.89E−02	6.11E−03
R side of head (including ear)	4.52E−03	1.76E−03	4.46E−03	1.76E−03	1.89E−02	6.11E−03
L side of head (including ear)	4.52E−03	1.76E−03	4.46E−03	1.76E−03	1.89E−02	6.11E−03
Front left thigh	6.00E−06	5.05E−06	6.00E−06	5.05E−06	3.58E−05	2.40E−05
Back left thigh	6.00E−06	5.05E−06	6.00E−06	5.05E−06	3.58E−05	2.40E−05
Front right thigh	6.00E−06	5.05E−06	6.00E−06	5.05E−06	3.58E−05	2.40E−05
Back right thigh	6.00E−06	5.05E−06	6.00E−06	5.05E−06	3.58E−05	2.40E−05
L knee and below	2.19E−06	1.85E−06	2.19E−06	1.85E−06	1.31E−05	8.77E−06
R knee and below	2.19E−06	1.85E−06	2.19E−06	1.85E−06	1.31E−05	8.77E−06
L side of face	4.52E−03	4.16E−04	4.46E−03	4.16E−04	1.89E−02	3.35E−03
R side of face	4.52E−03	4.16E−04	4.46E−03	4.16E−04	1.89E−02	3.35E−03
L side of neck	4.52E−03	1.76E−02	4.46E−03	1.76E−03	1.89E−02	6.11E−03
R side of neck	4.52E−03	1.76E−02	4.46E−03	1.76E−03	1.89E−02	6.11E−03
Back of head	4.52E−03	1.76E−03	4.46E−03	1.76E−03	1.89E−02	6.11E−03
Front of neck	4.52E−03	4.16E−04	4.46E−03	4.16E−04	1.89E−02	3.35E−03
Back of neck	4.52E−03	1.76E−02	4.46E−03	1.76E−03	1.89E−02	6.11E−03
Front torso: base of neck to end of sternum	7.26E−03	3.84E−04	7.26E−03	3.84E−04	4.67E−02	2.08E−03
Front torso: end of sternum to lowest rib	7.26E−03	3.84E−04	7.26E−03	3.84E−04	4.67E−02	2.08E−03
Front torso: lowest rib to iliac crest	7.26E−03	3.84E−04	7.26E−04	3.84E−05	4.67E−03	2.08E−04
Front torso: iliac crest to pubis	7.26E−04	3.84E−05	7.26E−04	3.84E−05	4.67E−03	2.08E−04
Back torso: base of neck to mid-back	7.26E−03	1.76E−02	7.26E−03	1.76E−02	4.67E−02	6.11E−02
Back torso: mid-back to lowest rib	7.26E−03	1.76E−02	7.26E−03	1.76E−02	4.67E−02	6.11E−02
Back torso: lowest rib to iliac crest	7.26E−03	1.76E−02	7.26E−04	1.76E−03	4.67E−03	6.11E−03
Back torso: buttocks (iliac crest and below)	7.26E−04	1.76E−03	7.26E−04	1.76E−03	4.67E−03	6.11E−03
Right torso: base of neck to end of sternum	4.46E−02	1.76E−02	4.46E−02	1.76E−02	1.89E−01	6.11E−02
Right torso: end of sternum to lowest rib	4.46E−02	1.76E−02	4.46E−02	1.76E−02	1.89E−01	6.11E−02
Right torso: lowest rib to iliac crest	4.46E−02	1.76E−02	4.46E−03	1.76E−03	1.89E−02	6.11E−03
Right torso: iliac crest to pubis (R hip)	4.46E−03	1.76E−03	4.46E−03	1.76E−03	1.89E−02	6.11E−03
Left torso: base of neck to end of sternum	1.96E−04	1.76E−02	1.96E−04	1.76E−02	1.41E−03	6.11E−02
Left torso: end of sternum to lowest rib	1.96E−04	1.76E−02	1.96E−04	1.76E−02	1.41E−03	6.11E−02
Left torso: lowest rib to iliac crest	1.96E−04	1.76E−02	1.96E−05	1.76E−03	1.41E−04	6.11E−03
Left torso: iliac crest to pubis (L hip)	1.96E−05	1.76E−03	1.96E−05	1.76E−03	1.41E−04	6.11E−03

a. The general method for calculating skin doses from chest projections is found in ORAUT-OTIB-0006, Section 6.0 and Tables B-4 and B-8 (ORAUT 2019a).
b. Procedures after 1989 were performed at LLNL (ORAUT 2006a); doses are as found in ORAUT (2010a).

Table 3-6. Organ doses from lumbar spine X-ray, 1956 to 1971 (rem).

Organ	Estimated dose[a,b] HVL = 2.5 mm Al (collimated) LAT	Estimated dose[a,b] HVL = 2.5 mm Al (collimated) AP
Thyroid	3.88E−05	2.84E−04
Eye/brain	3.88E−05	2.84E−04
Ovaries	7.10E−01[c]	5.60E−01[c]
Liver/gall bladder/spleen	7.10E−01[c]	5.60E−01[c]
Urinary bladder	7.10E−01[c]	5.60E−01[c]
Colon/rectum	7.10E−01[c]	5.60E−01[c]
Testes	5.60E−02	2.70E−02[c]
Lungs	5.44E−02	7.47E−02
Thymus	5.44E−02	7.47E−02
Esophagus	5.44E−02	7.47E−02
Stomach	7.10E−01[c]	5.60E−01[c]
Bone surfaces	7.10E−01[c]	5.60E−01[c]
Remainder	7.10E−01[c]	5.60E−01[c]
Female breast	5.05E−02	2.36E−02
Uterus	1.20E−01	2.71E−01
Bone marrow	8.54E−02	3.50E−02
Skin[d]	5.26E+00	1.28E+00

a. SSD = 63 cm for AP X-ray and 52 cm for LAT X-ray.
b. Image receptor size 35.6 cm by 43.2 cm.
c. Organ dose values for the testes and ovaries (and analogues) for lumbar spine reflect actual measurements reported in Lincoln and Gupton (1958).
d. Skin dose values include backscatter factors of 1.355 from Table B.8 of NCRP (1997).

Table 3-7. Skin doses from lumbar spine X-ray, 1956 to 1971.[a]

Skin area	LAT	AP
R front shoulder	5.26E−01	1.28E−01
R back shoulder	5.26E−01	2.79E−03
L front shoulder	2.31E−03	1.28E−01
L back shoulder	2.31E−03	2.79E−03
R upper arm to elbow	5.26E−01	1.28E−01
L upper arm to elbow	2.31E−03	1.28E−01
L hand	2.31E−03	1.28E+00[b]
R hand	5.26E−01	1.28E+00[b]
L elbow, forearm, wrist	2.31E−03	1.28E+00[b]
R elbow, forearm, wrist	5.26E−01	1.28E+00[b]
R side of head (including ear)	3.88E−05	2.84E−04
L side of head (including ear)	3.88E−05	2.84E−04
Front left thigh	2.31E−03	1.28E−01
Back left thigh	2.31E−03	2.79E−03
Front right thigh	5.26E−01	1.28E−01
Back right thigh	5.26E−01	2.79E−03
L knee and below	5.32E−04	2.76E−04
R knee and below	5.32E−04	2.76E−04
L side of face	3.88E−05	2.84E−04
R side of face	3.88E−05	2.84E−04
L side of neck	3.88E−05	2.84E−04
R side of neck	3.88E−05	2.84E−04
Back of head	3.88E−05	2.84E−04
Front of neck	3.88E−05	2.84E−04
Back of neck	3.88E−05	2.84E−04
Front torso: base of neck to end of sternum	5.44E−02	1.28E−01
Front torso: end of sternum to lowest rib	5.44E−02	1.28E+00

Skin area	LAT	AP
Front torso: lowest rib to iliac crest	5.44E−02	1.28E+00
Front torso: iliac crest to pubis	5.44E−02	1.28E+00
Back torso: base of neck to mid-back	5.44E−02	2.79E−03
Back torso: mid-back to lowest rib	5.44E−02	2.79E−02
Back torso: lowest rib to iliac crest	5.44E−02	2.79E−02
Back torso: buttocks (iliac crest and below)	5.44E−02	2.79E−02
Right torso: base of neck to end of sternum	5.26E−01	1.28E−01
Right torso: end of sternum to lowest rib	5.26E+00	1.28E+00
Right torso: lowest rib to iliac crest	5.26E+00	1.28E+00
Right torso: iliac crest to pubis (R hip)	5.26E+00	1.28E+00
Left torso: base of neck to end of sternum	2.31E−03	1.28E−01
Left torso: end of sternum to lowest rib	2.31E−02	1.28E+00
Left torso: lowest rib to iliac crest	2.31E−02	1.28E+00
Left torso: iliac crest to pubis (L hip)	2.31E−02	1.28E+00

a. The general method for calculating skin doses from chest projections is found in ORAUT-OTIB-0006, Section 6.0 and Tables B-5 and B-9 (ORAUT 2019a).
b. Guidance for these AP doses in 1971 is 10% of the entrance skin dose or 1.18E–01 rem (ORAUT 2019a).

Table 3-8. Distributions and corresponding statistical parameters for the dose to the B-lymphocytes.

Projection and period	Distribution	Parameter 1	Parameter 2	Parameter 3
PA chest 1956–1970	Weibull3	2.923411	0.002773	8.07816E−06
LAT chest 1956–1970	Weibull3	2.679824	0.003979	1.59961E−05
AP lumbar spine 1956–1971	Weibull3	3.118187	0.4762602	−0.002715842
LAT lumbar spine 1956–1971	Weibull3	3.171354	0.6082226	−0.002241317
PA chest 1971–1985	Weibull3	2.035671	0.001904	2.77200E−06
LAT chest 1971–1985	Weibull3	2.063026	0.003033	1.81402E−06
PA chest 1986–1989	Weibull3	2.0769196	0.008583	3.23658E−06
LAT chest 1986–1989	Weibull3	2.131524	0.016496	−2.07377E−06

In theory, a large number of factors can introduce uncertainties or affect X-ray machine output and dose to the worker. However, in practice, only five factors can be reasonably considered to have a meaningful or significant impact on dose uncertainty. These are (1) measurement error, (2) variation in applied kilovoltage, (3) variation in beam current, (4) variation in exposure time, and (5) SSD. The influence of other factors such as film speed, the use of screens, the use of grids, and development, while potentially variable, do not affect the beam output per se, except indirectly because they influence the machine settings (i.e., kVp, mA, and time). The lack of historical records for some of these measurements introduces uncertainty into the dose estimates that cannot be readily quantified, although there is no apparent reason to believe that practices at SNL-CA or its medical subcontractors were different from those at other facilities or from recommended standards of the medical community at the time. The following estimates of uncertainty associated with X-ray exposures are from ORAUT (2019a), which this analysis relied on for default information when site-specific records of X-ray machine settings could not be found (specifically, for filtration and HVL values). Other values were taken from available notes in claim files and were selected to be favorable to claimants whenever a range of values was found in the claim files.

ORAUT (2019a) reports that X-ray doses are derived largely 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 more current machinery could have a smaller uncertainty, ±2% is assumed to be conservative.

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

direct proportion. Large decreases in beam output would be readily detectable and would indicate the need for machine maintenance or, as a temporary measure, an increase in the current or voltage to provide the necessary intensity for proper radiography. ORAUT (2019a) estimates the variation in tube current to be approximately ±5% for this parameter.

Exposure time can significantly affect the dose received from radiography (exposure times are a fraction of second). Even a small variation in exposure time due to timer error can significantly change beam output. Because early X-ray machine timers are known to have been inaccurate, ORAUT (2019a) assumes uncertainty in beam output due to timers to be ±25%.

SSD can contribute to variability because the ESE is determined by this distance. Variations result from accuracy of positioning as well as worker size (thickness). As expressed in ORAUT (2019a), this is generally thought to vary by no more than a few centimeters, with an upper limit of 7.5 cm (±10%).

A potential source of uncertainty for SNL-CA is the number and type of X-rays taken. As noted above, reports indicate the performance of only an annual PA chest X-ray examination, but no official protocol has been found that would rule out the possibility of other X-ray views or more frequent chest examinations. At this time, dose reconstructors should assume a single annual PA chest X-ray for 1956 through 1989 [4]. Dose reconstructors should assign dose from the X-ray procedures actually listed on the preemployment X-ray record form. If the claim file is missing the preemployment X-ray record, the dose reconstructor should assign dose from a PA chest and AP and LAT lumbar spine as the default for the preemployment X-rays.

Another source of uncertainty is the lack of site-specific values for filtration and exposure time. While the claim files show a consistent notation of kVp and SID, interpretation was required to determine the beam current exposure before 1985. For all periods, Figure 3-1 was required to estimate air kerma. Filtration and HVL were not noted in claimant files, so the estimated values used in this document are favorable to claimants and consistent with practices during each period.

Consistent with ORAUT (2019a), this analysis relies on the statistical root mean square to estimate total uncertainty. The root mean square is the square root of the sum of the squares of the individual uncertainty values and equals 28.9%. An estimate of 30% uncertainty is favorable to claimants.

4.0 OCCUPATIONAL ENVIRONMENTAL DOSE

4.1 INTRODUCTION

The SNL-CA site is directly south of LLNL. The southern perimeter fence of LLNL is directly across the street from the northern perimeter fence of SNL-CA. Therefore, environmental dose is addressed in terms of potential exposures that could have occurred on the SNL-CA site as a result of both SNL-CA and LLNL operations. Aside from operations at the TRL, the internal exposures at SNL-CA are assumed to be due to LLNL operations alone. According to Holland (1998), no other measurable effluents of radionuclides from SNL-CA have existed. The external dose rate at the LLNL south perimeter, as measured by thermoluminescent dosimeters (TLDs), has been reported from 1967 to the present. These measurements are also considered in estimating external dose for SNL-CA.

4.1.1 Purpose

This section addresses the occupational environmental dose applicable to the SNL-CA site from the beginning of operations (1956) to the present. Occupational environmental dose refers to the radiation dose received outside of buildings, but on the SNL-CA site, as a result of ambient airborne radionuclides or ionizing radiation.

4.1.2 Scope

Internal and external exposures to radionuclides in the outdoor environment are considered separately in this section. Section 4.2 presents information necessary to estimate internal environmental dose; radionuclides of concern are first identified. The estimated source terms (release rates) for radionuclides that are considered potentially significant to internal environmental dose and internal exposure (yearly intake) are also addressed. Annual environmental reports for SNL-CA and LLNL form the basis of these estimates (Gudiksen et al. 1972, 1973; Silver et al. 1974 to 1980; Toy 1981; Auyong, Griggs, and Buddemeier 1982; Griggs, Myers, and Buddemeier 1984; Griggs and Buddemeier 1986; Holland, Buddemeier, and Brekke 1987; Holland and Brekke 1988; Kamelgarn 1989; Gallegos et al. 1990; Schwoegler et al. 1991; Gallegos et al. 1992 to 1994; Harrach et al. 1995 to 1998; Larson et al. 1999, 2000; Biermann et al. 2001; Gallegos et al. 2002; Sanchez et al. 2003, 2004; Peterson et al. 2005; LRL 1962a,b, 1963 to 1971; Devlin 1986 to 1988; Siegfriedt 1989; Brekke 1990,1991; Brekke and Holland 1992 to 1995; Holland and Brekke 1996; Holland 1997 to 2002; Larsen 2003 to 2005; SNL 1982, 1983, 1984).

Section 4.3 contains information necessary for estimating external environmental dose. Ambient external dose rates, reported in annual environmental reports for LLNL and SNL-CA, were used to estimate dose rates for the operational period of SNL-CA.

Section 4.3 also considers uncertainties in the information provided for estimating occupational environmental dose. The discussion addresses sources of uncertainty and provides quantitative information where possible.

4.2 INTERNAL DOSE FROM ONSITE ATMOSPHERIC RADIONUCLIDE CONCENTRATIONS

4.2.1 Radionuclides of Concern

The only detectable effluents from the SNL-CA site occurred during operations of the TRL, when ^{3}H was released (Section 2.3.2); however, such tritium releases provided annual doses of less than 1 mrem/yr (<0.001 rem/yr) and are considered insignificant. Releases of DU from the SNL-CA site are not considered a significant source of environmental exposure at the SNL-CA. Such releases would only occur during machining operations, but according to Brekke (1990) all operations at SNL-CA using DU were equipped with exhaust air systems with absolute filters at that time. Furthermore, machining operations, which began in 1971 (Adolphson 1972), were monitored closely for airborne contamination; operations were immediately stopped if airborne contamination was detected (SNL 1989). These mitigating factors would prevent the contribution of DU to any environmental intakes.

However, the presence of measurable concentrations of airborne particulate radionuclides in the LLNL south perimeter area, nearly adjacent to the north perimeter area of SNL-CA, requires that these radionuclides be considered as potentially significant contributors to environmental dose on the SNL-CA site. Environmental tritium measurements for LLNL for all years indicate environmental doses of less than 1 mrem (<0.001 rem) and are not considered significant (ORAUT 2020). LLNL has processed and handled a number of radionuclides, including uranium and transuranic elements, mixed fission products, and accelerator-produced isotopes. Plutonium-239 and isotopes of uranium have been identified as radionuclides of significance in ORAUT-TKBS-0035-4, *Lawrence Livermore National Laboratory – Occupational Environmental Dose* (ORAUT 2020), consistent with the list of radionuclides identified by the LLNL environmental monitoring program as representing more than 90% of the LLNL radioactive materials inventory.

Before considering any or all of the particulate radionuclides from the LLNL site as isotopes of significance at SNL-CA in relation to environmental dose, the concentrations at the LLNL perimeter

nearest to SNL-CA and the potential associated doses were first evaluated. Between 1961 and 1970, concentrations of gross alpha and gross beta were measured at one or more perimeter locations near the south side of the LLNL site, as well at several offsite locations in the Livermore valley (LRL 1962a, 1963 to 1970). Isotope-specific data were not reported during this period. The reported data included contributions from naturally occurring alpha- and beta-emitting radionuclides. By comparing average offsite measured concentrations of gross alpha- and beta-emitting airborne particulate radionuclides with those measured at the southern perimeter, net concentrations of these particulates were calculated. The maximum net beta concentration during this period was 3×10^{-2} Bq/m^3 (8.1×10^2 pCi/L); the maximum net alpha concentration was 5.9×10^{-5} Bq/m^3 (1.6 pCi/L). When not zero (i.e., when the concentrations at the perimeter were not less than average measured offsite concentrations), committed organ doses associated with the alpha- and beta-emitting particulate radionuclides were calculated, assuming an annual inhalation rate of 2,400 m^3, that the alpha-emitting radionuclides were comprised wholly of ^{234}U, and the beta-emitting radionuclides were comprised wholly of ^{90}Sr (a fission product). Dose factors were selected on the basis of which organ received the highest dose (i.e., the maximum organ dose was calculated). The representative radionuclides were selected based on their relatively higher organ dose factors in comparison with other possible representative radionuclides, so that the analysis is not likely to overlook potentially significant contributors to internal dose. A comparison of the gross alpha and gross beta dose calculations indicated that the organ dose associated with beta-emitting radionuclides generally contributes less than 5% of the committed dose but always contributes less than 1 mrem to the yearly committed organ dose associated with environmental exposures for this period. The committed doses associated with gross alpha for a 1-year intake ranged from 0 to 140 mrem, the latter based on the assumption that the gross alpha intake could be represented by ^{234}U.

From 1971 to the present, concentrations of particulate $^{239/240}$Pu, ^{235}U, ^{238}U, and gross beta emitters have been measured at a south LLNL perimeter location directly across the street from SNL-CA (Gudiksen et al. 1972, 1973; Silver et al. 1974 to 1980; Toy 1981; Auyong, Griggs, and Buddemeier 1982; Griggs, Gonzalez, and Buddemeier 1983; Griggs, Myers, and Buddemeier 1984; Griggs, Meyers, and Buddemeier 1985; Griggs and Buddemeier 1986; Holland, Buddemeier, and Brekke 1987; Holland and Brekke 1988; Kamelgarn 1989; Gallegos et al. 1990; Schwoegler et al. 1991; Gallegos et al. 1992 to 1994; Harrach et al. 1995 to 1998; Larson et al. 1998, 1999, 2000; Althouse et al. 2000, Biermann et al. 2001; Gallegos et al. 2001, 2002; Sanchez et al. 2002, 2003, 2004; LLNL 2004 to 2017; Peterson et al. 2005). Tritium was measured by LLNL at this location since 1973. At this location (labeled CAFÉ in LLNL annual environmental reports), the maximum net beta emitter inhalation dose is estimated to be 0.03 mrem/yr, assuming that ^{90}Sr is the representative radionuclide. The maximum concentration of ^{239}Pu between 1971 and 2004 was 2.6×10^{-6} Bq/m^3 (7.0×10^{-2} pCi/L), which corresponds to an inhalation intake of 6.3×10^{-3} Bq/yr , assuming a yearly inhalation rate of 2,400 m^3/yr. The maximum committed organ dose from this annual intake is estimated as 1.1 mrem. At the same location, the maximum concentrations of ^{235}U and ^{238}U were 1.6×10^{-12} g/m^3 and 2.2×10^{-10} g/m^3, respectively. These concentrations correspond to annual intakes of 3.1×10^{-4} Bq/yr and 6.4×10^{-3} Bq/yr of ^{235}U and ^{238}U, respectively. Making the assumption that these intakes are both of ^{234}U is favorable to the claimant; the corresponding committed maximum organ dose for a 1-year intake is 6.7 mrem.

These measured concentration data and dose calculations indicate that particulate airborne beta-emitting radionuclides from LLNL are not significant contributors to environmental occupational dose on the SNL-CA site. This is consistent with the finding in LLNL environmental reports, which indicate that the gross beta activity is due to global fallout and that it fluctuates in a manner typical of that source (Gudiksen et al. 1972, 1973; Silver et al. 1974 to 1980; Toy 1981; Auyong, Griggs, and Buddemeier 1982; Griggs, Myers, and Buddemeier 1984; Griggs and Buddemeier 1986; Holland, Buddemeier, and Brekke 1987; Holland and Brekke 1988; Kamelgarn 1989; Gallegos et al. 1990; Schwoegler et al. 1991; Gallegos et al. 1992 to 1994; Harrach et al. 1995 to 1998; Larson et al. 1999, 2000; Biermann et al. 2001; Gallegos et al. 2002; Sanchez et al. 2003, 2004; Peterson et al. 2005).

The alpha-emitting radionuclides ^{234}U and ^{239}Pu (represented as gross alpha before 1971) from LLNL are retained as potentially significant contributors to internal environmental dose at SNL-CA. Inhalation intakes for these radionuclides are addressed in Section 4.2.3 below.

4.2.2 Source Terms for Internal Dose

No onsite environmental sources or outdoor concentrations of radionuclides were reported for SNL-CA before the beginning of operation of the TRL in 1979. Release of radionuclides from activities at LLNL could have affected intakes by workers at SNL-CA, as noted in Section 4.2.1 above. The assumption that the nearest perimeter concentrations at the LLNL site represent the onsite concentrations at SNL-CA before operation of the TRL is favorable to the claimant, as a decrease in air concentration with distance from the LLNL perimeter would likely occur. From April through September the prevailing winds are from the west and southwest and are variable throughout the remainder of the year (Holland and Brekke 1988); therefore, this assumption is most favorable to the claimant during these months.

4.2.3 Annual Intake of Radioactivity

Inhalation intakes of airborne particulate ^{234}U and ^{239}Pu are estimated in this section.

To calculate inhalation intake, it was necessary to consider the onsite air concentrations of ^{234}U and ^{239}Pu due to the presence of these isotopes near the LLNL south boundary (closest to the SNL-CA).

Intakes were calculated by multiplying the relevant concentrations by an assumed inhalation rate of 2,400 m^3/yr. For airborne particulates (i.e., ^{234}U and ^{239}Pu), no particle size information was available; therefore, the default ICRP Publication 66 value of 5-µm activity median aerodynamic diameter is recommended (ICRP 1994). Further, no solubility information is available for airborne uranium or plutonium particulates; therefore, assumed solubility should be selected based on what is most favorable to the claimant in light of the organ of interest.

4.2.3.1 Inhalation Intakes

The following methodological information is summarized in Table 4-1. Calculated intakes are provided in Tables 4-2 and 4-3. The basis for the intake values in Tables 4-2 and 4-3 is documented in ORAUT (2020).

Table 4-1. Summary of methodology for estimating intakes of ^{3}H, ^{234}U, and ^{239}Pu.

Radionuclide	Applicable period	Method used
H-3	1956–1978, 1997–2018	Potential environmental H-3 releases from LLNL from all sources were determined to provide internal doses of less than 1 mrem/year (<0.001 rem/year). They are not considered significant for environmental dose for LLNL employees and are, therefore, not considered significant for employees at SNL-CA (ORAUT 2020).
H-3	1979–1996	Potential intakes during the operation of the TRL, along with intake data from all sources at LLNL (ORAUT 2020), were evaluated and determined to result in potential internal doses of less than 1 mrem/year (<0.001 rem/year). They are not considered significant for environmental dose for employees at SNL-CA.
U-234	1956–1960	No data available for this period.
U-234	1961–1970	Reported south LLNL perimeter gross alpha concentration measurements were corrected for average Livermore valley background contributions and multiplied by an inhalation intake rate of 2,400 m^3/yr to estimate maximum SNL-CA intakes (Bq/yr).

Radionuclide	Applicable period	Method used
U-234	1971–2018	Reported south LLNL perimeter U-235 and -238 activity concentrations (Bq/m^3) were multiplied by an inhalation intake rate of 2,400 m^3/yr to estimate maximum SNL-CA intakes (Bq/yr). The unreported U-234 concentrations were addressed by assuming U-234 intake was equivalent to U-238. Activity intakes for all radionuclides are added and assumed to be U-234.
Pu-239	1956–1960	No data available for this period.
Pu-239	1961–1970	Reported south LLNL perimeter gross alpha concentration measurements were corrected for average Livermore valley background contributions and multiplied by an inhalation intake rate of 2,400 m^3/yr to estimate maximum SNL-CA intakes (Bq/yr).
Pu-239	1971–2018	Reported south LLNL perimeter Pu-239 activity concentrations (Bq/m^3) were multiplied by an inhalation intake rate of 2,400 m^3/yr to estimate maximum SNL-CA intakes (Bq/yr).

Table 4-2. Sitewide annual median inhalation intakes (Bq/yr), 1956 to 1970.[a,b]

Year	U-234 or Pu-239[c]
1956	(d)
1957	(d)
1958	(d)
1959	(d)
1960	(d)
1961	1.24E-01
1962	1.36E-01
1963	5.77E-02
1964	6.39E-02
1965	0.00[e]
1966	0.00[e]
1967	0.00[e]
1968	0.00[e]
1969	0.00[e]
1970	0.00[e]

a. Assumes an inhalation rate of 2,400 m^3/yr.
b. Intakes are assigned as lognormal distributions, with a geometric standard deviation (GSD) of 3.
c. Gross alpha is reported for 1961 to 1970; recommend assuming the isotope of either U-234 or Pu-239 that gives highest dose to the organ of interest.
d. No measurement results were reported for these years.
e. A zero value indicates the measured concentration was less than or equal to the offsite background concentration.

Table 4-3. Sitewide annual median inhalation intakes (Bq/yr), 1971 to 2018.[a,b]

Year	U-234[c]	Pu-239[c]
1971	3.63E-03	6.30E-03
1972	6.26E-03	2.84E-03
1973	5.75E-03	1.51E-03
1974	5.07E-03	2.93E-03
1975	4.82E-03	2.04E-03
1976	5.63E-03	7.99E-04
1977	7.63E-03	2.13E-03

Year	U-234[c]	Pu-239[c]
1978	1.07E-03	2.66E-03
1979	5.45E-03	1.51E-03
1980	3.75E-03	4.44E-04
1981	7.44E-03	1.42E-03
1982	6.77E-03	4.44E-04
1983	9.31E-03	2.17E-03
1984	6.01E-03	3.55E-04
1985	5.57E-03	1.78E-04
1986	4.89E-03	1.15E-04
1987	5.88E-03	7.10E-05
1988	1.37E-02	7.99E-05
1989	4.53E-03	6.04E-05
1990	5.92E-03	1.24E-04
1991	6.12E-03	1.69E-04
1992	5.27E-03	0.00[d]
1993	4.37E-03	8.64E-05
1994	3.41E-03	8.18E-05
1995	2.82E-03	5.88E-05
1996	2.86E-03	5.76E-05
1997	3.04E-03	1.56E-05
1998	2.13E-03	1.42E-05
1999	4.11E-03	1.32E-05
2000	0.00[d]	2.18E-05
2001	0.00[d]	9.19E-06
2002	2.43E-03	5.74E-06
2003	1.45E-03	5.98E-06
2004	1.38E-03	7.39E-06
2005	9.58E-04	7.73E-05
2006	1.03E-03	3.36E-06
2007	1.07E-03	0.00[d]
2008	1.30E-03	0.00[d]
2009	1.12E-03	5.98E-06
2010	6.51E-04	6.77E-06
2011	8.64E-04	1.93E-06
2012	1.25E-03	0.00[d]
2013	1.01E-03	2.76E-06
2014	1.01E-03	2.10E-06
2015	8.14E-04	0.00[d]
2016	8.58E-04	0.00[d]
2017	9.39E-04	2.19E-03
2018	7.95E-04	0.00[d]

a. Assumes an inhalation rate of 2,400 m^3/yr.
b. Intakes are assigned as lognormal distributions, with a GSD of 3.
c. Intakes based on LLNL south perimeter concentrations; see Table 4-1.
d. Median activities for uranium and plutonium samples were negative and are reported as zero.

Particulate Intakes (^{239}Pu and ^{234}U)

Measured concentrations of ^{239}Pu, ^{235}U, and ^{238}U at the south perimeter of the LLNL, near the SNL-CA site, were reported in annual environmental reports from 1971 through 2018 (Gudiksen et al. 1972, 1973; Silver et al. 1974 to 1980; Toy 1981; Auyong, Griggs, and Buddemeier 1982; Griggs, Gonzalez, and Buddemeier 1983; Griggs, Myers, and Buddemeier 1984; Griggs, Meyers, and Buddemeier 1985; Griggs and Buddemeier 1986; Holland, Buddemeier, and Brekke 1987; Holland and Brekke 1988;

Kamelgarn 1989; Gallegos et al. 1990; Schwoegler et al. 1991; Gallegos et al. 1992 to 1994; Harrach et al. 1995 to 1998; Larson et al. 1998, 1999, 2000; Althouse et al. 2000, Biermann et al. 2001; Gallegos et al. 2001, 2002; Sanchez et al. 2002, 2003, 2004; LLNL 2004 to 2017; Peterson et al. 2005). Intakes of ^{239}Pu for these years (Table 4-3) were calculated assuming the SNL-CA site concentration could be approximated by this south perimeter concentration. Intakes of uranium for these years (Table 4-3) were calculated by summing the intakes of ^{235}U and ^{238}U (Bq/yr) and an estimated ^{234}U intake associated with the perimeter concentrations. The ^{234}U intake was estimated by assuming it is equal to that of ^{238}U, which is approximately the case with natural uranium. The ^{235}U:^{238}U ratios on the LLNL main site perimeter have been reported as representative of natural uranium (Gallegos et al. 1994). The total activity intake of uranium is then assumed to be represented by ^{234}U, which is favorable to the claimant because most of the uranium activity (99%) is associated with ^{238}U and ^{234}U and dose factors for ^{234}U are higher.

Before 1971, only gross alpha measurements were available (LRL 1962a, 1963 to 1971). From 1961 through 1970, the net alpha measurements, which were calculated by subtracting the average offsite gross alpha measurements (i.e., background values) from the reported values, were used to derive intakes of either ^{234}U or ^{239}Pu (Table 4-2). Net concentrations calculated to be less than zero were assumed to be zero. The assumed radionuclide should be the one that gives the highest dose to the organ of interest. For the 5 years of operation before 1961, there are no measurements available with which to estimate the intakes of ^{234}U and ^{239}Pu.

4.3 EXTERNAL EXPOSURE TO ONSITE ATMOSPHERIC RADIONUCLIDE CONCENTRATIONS

4.3.1 Locations of Concern

Radionuclides present on the SNL-CA site with the potential to cause elevated ambient external exposures above background levels are restricted to those associated with the Radiography Building (Brekke and Holland 1993). A 1975 aerial survey of the LLNL and SNL-CA in 1975 found gamma-emitting radioactivity in excess of background levels in the vicinity of Building 9143 (the Radiography Building at the time) and to a much lesser extent, in the vicinity of a waste holding area known to contain DU and thorium (Building 9122), and a material storage vault known to contain DU, thorium, and small amounts of shielded ^{60}Co, ^{133}Ba, and ^{235}U (Building 921, incorrectly referred to as B-291 in the report; Tipton 1977). The highest estimated exposure rate at the center of the Radiography Building (as seen in the flyover) in excess of background gamma was 40 to 70 µR/hr (100 to 175 mrem/yr) for a 2,500 hr/yr occupational exposure. The highest values for the holding area and storage vaults were 2.0 to 8 µR/hr (5 to 20 mrem/yr) for a 2,500 hr/yr occupational exposure. It was indicated in the 1977 annual monitoring report (Silver et al. 1978) that none of the elevated areas posed a radiation hazard to workers. Further, the survey indicated that the sources were restricted to work areas where access was limited. Therefore, from the standpoint of environmental exposure, there were no areas identified in the survey containing radionuclides that posed a source of elevated ambient external exposure to workers.

As with the internal exposures, consideration must be given to external exposures from activities at the LLNL site in addition to those at the SNL-CA site. As early as 1964, LLNL measured perimeter external radiation (LRL 1965). Fluoroglass dosimeters were used at that time that had a limit of detection of 50 mrem. The reported dose rates were reported to be less than 0.01 mR/hr, which corresponds to less than 88 mrem/yr for continuous exposure. The use of TLDs apparently began in 1967 (LRL 1968). In 1971, a few perimeter locations were identified at which exposure rates were considered elevated above background (Gudiksen et al. 1972). One of these locations (Location 5 – neutron dosimeter) was adjacent to the LLNL cyclotron building and is at the south perimeter of the LLNL site (directly across the street from the north perimeter of SNL-CA). Therefore, this LLNL perimeter location (south location) was considered in evaluating external exposures. Environmental

neutron measurements were also made at this location and reported in annual reports beginning in 1973. These are discussed in Section 4.3.3 below.

4.3.2 Gamma-Emitting Radionuclides

The use of TLDs to measure environmental radiation exposure at the SNL-CA site perimeter apparently began around 1989, which was the first time that the five SNL-CA perimeter TLDs (Figure 4-1) are mentioned in annual environmental reports (Brekke 1990). Before that time, the site relied on LLNL perimeter and offsite measurements because the latter encompassed the SNL-CA perimeter (Figures 4-2 and 4-3). The estimated average and maximum dose external dose rates are listed in Table 4-4 and are based on both LLNL and SNL-CA perimeter measurements. The values are applicable to an exposure duration of 2,500 hr/yr (50 hr/wk, 50 wk/yr). The basis for the external doses in Table 4-4 is documented in ORAUT (2020).

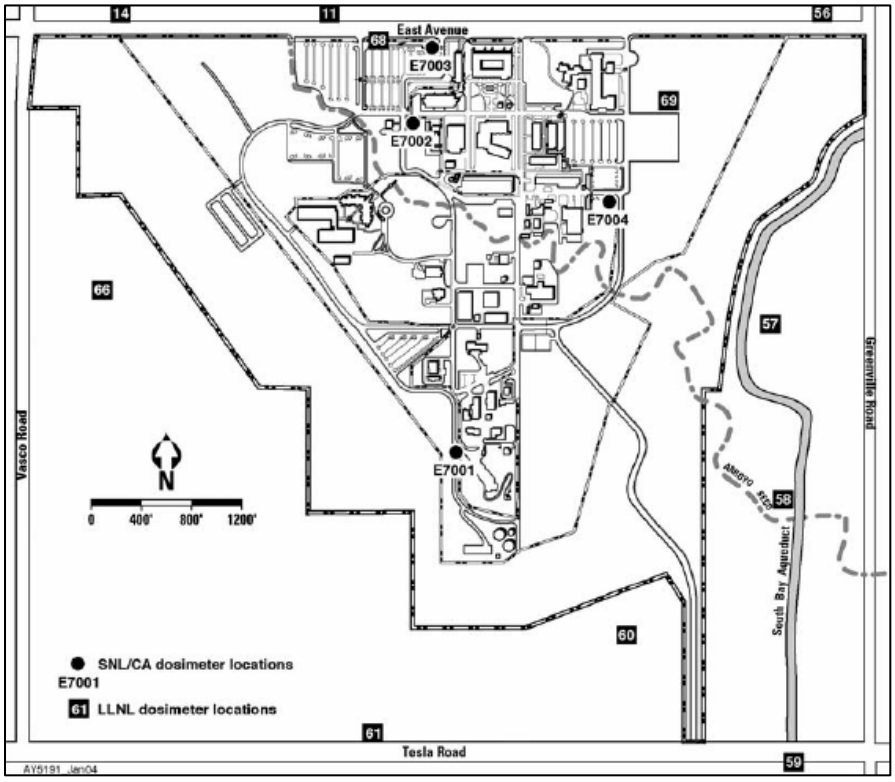


Figure 4-1. TLD locations since 1989.

The data preference used in determining the values included in Table 4-4 was to include SNL-CA measurements when available, but this only occurred from 1990 to 1994 (Brekke 1991; Brekke and Holland 1992 to 1995). Before 1990, south LLNL perimeter measurements were used to estimate SNL-CA exposure rates. This provides a maximum estimate of the contribution of LLNL exposure rates to the SNL-CA rates. This south perimeter value is also a reasonable estimate of the expected environmental exposure rates for the SNL-CA. The 1975 aerial survey indicated this measurement point coincided with the LLNL accelerator and therefore had a slightly elevated exposure rate on the order of that seen for the storage vaults and holding area at SNL-CA (Tipton 1977). Because most of the SNL-CA area surveyed in 1975 did not show exposure rates elevated above background, this is an assumption that is favorable to the claimant.

There were no reliable measurements for either SNL-CA or the south perimeter LLNL location before 1967. The values for 1967 to 1969 in Table 4-4 assume that the “experimental physics facility” mentioned in the corresponding annual reports (LRL 1968 to 1970) represents the south perimeter

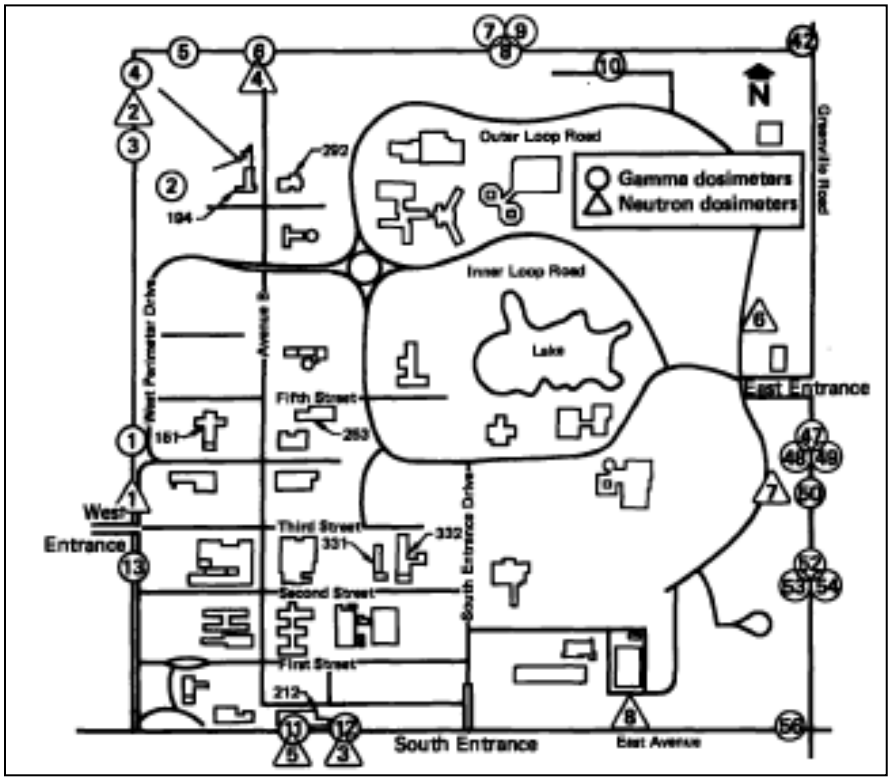


Figure 4-2. Location of LLNL perimeter gamma and neutron dosimeters (Griggs and Buddemeier 1986).

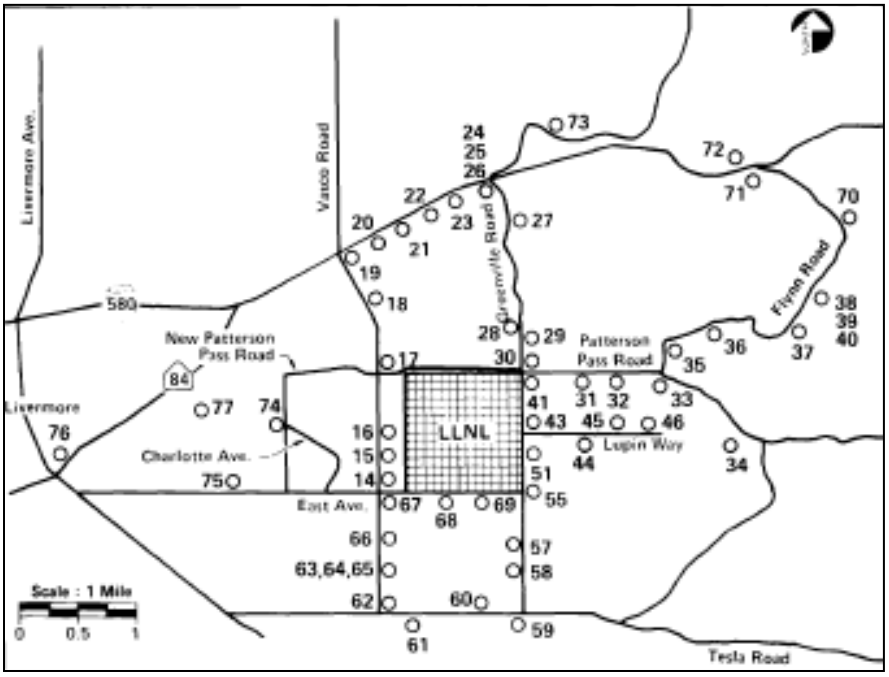


Figure 4-3. Location of LLNL offsite gamma dosimeters (Holland and Brekke 1988).

location that is labeled Location 5 from 1970 to 1980 (LRL 1971, Gudiksen et al. 1972, 1973; Silver et al. 1974 to 1980; Toy 1981), but is relabeled Location 11 after 1980 (Auyong, Griggs, and Buddemeier 1982; Griggs, Myers, and Buddemeier 1984; Griggs and Buddemeier 1986; Holland, Buddemeier, and Brekke 1987; Holland and Brekke 1988; Kamelgarn 1989; Gallegos et al. 1990;

Table 4-4. External gamma radiation dose based on 2,500 hr/yr[a] exposure duration (mrem/yr).

Year	Average perimeter[b]	Error[c]	Bounding dose rate[d]
1956	51[e]	15	66
1957	51[e]	15	66
1958	51[e]	15	66
1959	51[e]	15	66
1960	51[e]	15	66
1961	51[e]	15	66
1962	51[e]	15	66
1963	51[e]	15	66
1964	51[e]	15	66
1965	51[e]	15	66
1966	51[e]	15	66
1967	11	3	15
1968	120	36	156
1969	24	7	31
1970	40	12	52
1971	25	7	32
1972	35	10	45
1973	27	8	36
1974	39	12	51
1975	90	27	118
1976	84	25	109
1977	65	19	84
1978	27	8	35
1979	27	8	36
1980	23	7	30
1981	16	5	23
1982	19[f]	6	25
1983	21	6	27
1984	22[f]	7	28
1985	23	7	30
1986	17	5	23
1987	17	5	22
1988	16	5	21
1989	15	5	20
1990	15	4	19
1991	16	5	20
1992	16	5	20
1993	15	5	20
1994	21	6	27
1995	16	5	21
1996	16	5	21
1997	17	5	22
1998	17	5	22
1999	17	5	22
2000	16	5	21
2001	16	5	22
2002	19	6	25
2003	16	2	18
2004	16	2	18
2005	17	2	19
2006	17	2	18
2007	17	3	19
2008	16	2	18
2009	17	1	18
2010	16	1	17
2011	16	2	18
2012	16	2	18
2013	17	2	18
2014	16	2	18
2015	16	2	18
2016	16	2	18
2017	16	1	17
2018	17	1	18

a. 2,500 hr/yr taken from ORAUT (2019b).
b. Until 1990, unless otherwise noted, values are the south perimeter LLNL dose rate; from 1990 through 2002, values are the average of SNL-CA perimeter dosimeters; from 2003 through 2018, values are the average of the LLNL perimeter dosimeters.
c. Error assumed to be ±30% of the higher of the average perimeter (ORAUT 2012b) through 2002. From 2003, the error is the difference between the LLNL maximum and average values.
d. Bounding dose rate is the average perimeter value plus error term. Bounding dose rates can vary due to rounding of average perimeter and error values.
e. Assumed average dose rate estimated for the perimeter from 1967 through 1977 – no measurements reported for the LLNL south perimeter or for SNL-CA from 1956 through 1966.
f. Assumed the average of the previous year and the year after – missing annual environmental reports for 1982 and 1984.

Schwoegler et al. 1991; Gallegos et al. 1992 to 1994; Harrach et al. 1995 to 1998; Larson et al. 1999, 2000; Biermann et al. 2001; Gallegos et al. 2002; Sanchez et al. 2003, 2004; Peterson et al. 2005; Matthews et al. 2006, 2007; Gallegos et al. 2008, 2009; Jones et al. 2010 through 2014; Rosene et al. 2015 through 2018). This is a reasonable assumption because this location at that time corresponded to the location of the LLNL cyclotron.

The Table 4-4 exposure estimates for 1970 through 1980 correspond to measurements at the LLNL south perimeter TLD Location 5 and, from 1981 through 1989, to TLD Locations 11 and 12, with the exception of the 1982 and 1984 values, which were estimated by averaging 1981, 1983, and 1985

values due to the inability to find annual reports for 1982 and 1984. Last, SNL-CA TLD measurements are included for the years they were reported: 1990 through 1994. For these years, the "average perimeter" dose rate in Table 4-4 represents the average of the reported SNL-CA measurements. After 1994, the average perimeter dose rate was estimated by averaging the 5 years' worth of SNL-CA data.

Background radiation measurements for the Livermore valley have been reported in LLNL annual reports since 1971 (Gudiksen et al. 1972, 1973; Silver et al. 1974 to 1980; Toy 1981), but is relabeled Location 11 after 1980 (Auyong, Griggs, and Buddemeier 1982; Griggs, Myers, and Buddemeier 1984; Griggs and Buddemeier 1986; Holland, Buddemeier, and Brekke 1987; Holland and Brekke 1988; Kamelgarn 1989; Gallegos et al. 1990; Schwoegler et al. 1991; Gallegos et al. 1992 to 1994; Harrach et al. 1995 to 1998; Larson et al. 1999, 2000; Biermann et al. 2001; Gallegos et al. 2002; Sanchez et al. 2003, 2004; Peterson et al. 2005; Matthews et al. 2006, 2007; Gallegos et al .2008, 2009; Jones et al. 2010 through 2014; Rosene et al. 2015 through 2018).

Figure 4-4 is a summary of the quarterly results from 1988 through 1996; it compares LLNL average perimeter measurements and average LLNL Site 300 measurements to the offsite measurements. From Figure 4-4, it is evident that there have been only minor quarterly fluctuations around the value of 14 mrem/quarter but no significant long-term trends of either the background measurements or the LLNL perimeter measurements. The average yearly onsite ambient dose rate, which was calculated from the yearly rate for these 9 years (Harrach et al. 1997), is 57 mrem/yr for continuous exposure or 16 mrem/yr for a 2,500-hr/yr occupational exposure, as reflected in Table 4-4.

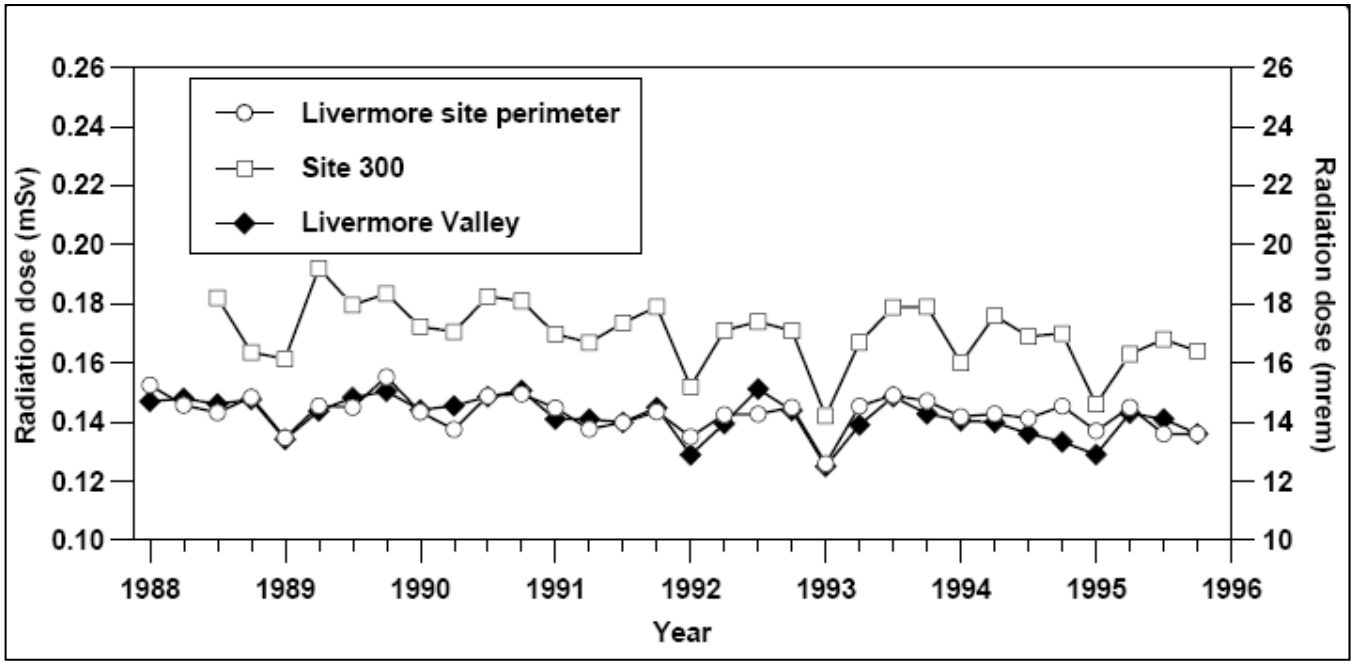


Figure 4-4. Livermore valley radiation background measurements in comparison with annual average measurements at LLNL site perimeter and LLNL Site 300 (Harrach et al. 1997).

4.3.3 Neutron Exposure

The Insulating Core Transformer (ICT) (also known as Rotating Target Neutron Source I) accelerator began operation in 1966 in Building 212 at LLNL (Peterson 2005). This facility was known to be responsible for elevated levels of environmental neutrons at the LLNL south perimeter (across the street from the north perimeter of SNL-CA) (Silver et al. 1974 to 1980; Toy 1981; Auyong, Griggs, and Buddemeier 1982; Griggs, Myers, and Buddemeier 1984; Griggs and Buddemeier 1986; Holland,

Buddemeier, and Brekke 1987; Holland and Brekke 1988). The increased neutron dose rate was attributed to operation of the ICT (also referred to as a 14-MeV neutron generator in LLNL annual reports). Environmental neutron monitoring began at LLNL in 1973 but was discontinued in 1994 because the operations responsible for neutron radiations were discontinued (Harrach et al. 1996). Measurements were initially made at Location 5 (Figure 4-2) (Silver et al. 1974), but a monitor at Location 3 (originally called 5a) was added in 1975 (Silver et al. 1976). By 1987, the dose rates were at background neutron levels, which is approximately 4 mrem/yr for continuous exposure (Harrach et al. 1995).

Although the dose rates were fairly elevated at the measurement location for several years, the dose rate at the SNL-CA perimeter would be considerably less due largely to dilution as the beam spread increases with distance from the source. The distance from the source to the monitoring locations on the LLNL perimeter was approximately 17 m (56 ft) (Willhoite 1979). Assuming that this is also the approximate distance to the nearest SNL-CA perimeter (which currently is across a four-lane street with shoulders on either side), the neutron dose rate at the SNL-CA perimeter would be approximately one-fourth the LLNL perimeter dose rate according to the inverse square law. The resulting estimated dose rates at the SNL-CA north perimeter in Table 4-5 were also corrected for an occupational exposure duration of 2,500 hr/yr and background contributions. These values are favorable to the claimant because the dose rate drops off fairly rapidly throughout other areas of the SNL-CA site. Due to the lack of information for years before 1973 about the operation of the ICT, it was assumed that the 1973 value was representative of all previous years of operation (i.e., 1966 to 1972). The basis for the external doses in Table 4-5 is documented in ORAUT (2020).

Table 4-5. Elevated neutron dose due to LLNL perimeter neutron source, based on 2,500 hr/yr exposure duration (mrem/yr).[a]

Year	North perimeter dose[b]	Error[c]	Bounding dose[d]
1966	18[e]	5	23
1967	18[e]	5	23
1968	18[e]	5	23
1969	18[e]	5	23
1970	18[e]	5	23
1971	18[e]	5	23
1972	18[e]	5	23
1973	18	5	23
1974	26	8	34
1975	50	15	65
1976	43	13	55
1977	39	12	51
1978	9	3	12
1979	6	2	8
1980	6	2	8
1981	2	1	3
1982	8[f]	2	10
1983	8	2	10
1984	8[f]	2	10
1985	<1	N/A[g]	1.3[h]
1986	2	1	3
1987	<1	N/A[g]	1.3[h]
1988	<1	N/A[g]	1.3[h]
1989	<1	N/A[g]	1.3[h]
1990	<1	N/A[g]	1.3[h]
1991	<1	N/A[g]	1.3[h]
1992	<1	N/A[g]	1.3[h]

Year	North perimeter dose[b]	Error[c]	Bounding dose[d]
1993	<1	N/A[g]	1.3[h]
1994	<1	N/A[g]	1.3[h]

a. Reported for years neutron dose rate was believed, or unknown, to have exceeded background levels.
b. Value for south LLNL perimeter dose rate at Location 3 or 5, which was corrected for distance to SNL-CA, background, and assumed exposure time of 2,500 hr/yr.
c. Error assumed to be ±30% of the average perimeter dose (ORAUT 2012b).
d. Bounding dose rate is the average perimeter value plus error term. Bounding dose rates may vary due to rounding of average perimeter and error values.
e. Assumed value reported for 1973 applied to previous years back to 1966.
f. Assumed the 1983 value; annual environmental reports for 1982 and 1984 not found.
g. N/A = not applicable.
h. Bounding dose rates for 1985 and 1987 are based on rounding up north perimeter dose to 1.000 mrem/yr and adding a 30% error, as described above.

To be favorable to claimants and consistent with ORAUT (2010b), a neutron energy range of 0.1 to 2.0 MeV should be chosen along with an International Commission on Radiological Protection Publication 60 weighting factor of 1.91 (ICRP 1991).

5.0 INTERNAL DOSIMETRY

5.1 INTRODUCTION

5.1.1 Purpose

The purpose of this section is to describe internal dosimetry practices at SNL-CA to support dose reconstructions under EEOICPA.

5.1.2 Scope

Section 5.2 summarizes potential internal exposures to radionuclides. Section 5.3 describes the bioassay monitoring programs SNL-CA used over the years, and Section 5.4 discusses laboratory procedures and minimum detectable intakes. Section 5.5 discusses the results of the bioassay programs in terms of dose. Section 5.6 provides a method of calculating dose from urine bioassay data, and Section 5.7 discusses airborne radionuclide concentrations. Section 5.8 discusses estimates of unmonitored dose, and Section 5.9 describes the radiation dosimetry reports. Section 5.10 provides summary tables of the above information.

5.1.3 Special Exposure Cohort

NIOSH has determined that it is not feasible to reconstruct internal dose from October 1, 1957, through December 31, 1994, due to a lack of sufficient information, which includes biological and workplace monitoring data and radiological source information that would allow it to estimate potential internal exposure to tritium, highly enriched uranium (HEU) and DU, uranium tritides and hydrides, thorium, and classified activities (NIOSH 2013). Therefore, this period has been included in the SEC.

Dose reconstruction guidance in this document for this period is presented to provide a technical basis for partial dose reconstructions for nonpresumptive cancers not covered in the SEC class or for claims with less than 250 working days in the SEC period.

Although NIOSH found that it is not possible to reconstruct internal radiation doses completely for the proposed class, it intends to use internal monitoring data that might become available for an individual claim (and that can be interpreted using existing NIOSH dose reconstruction processes or procedures). Therefore, dose reconstructions for individuals employed at SNL-CA from October 1,

1957, through December 31, 1994, but who do not qualify for inclusion in the SEC, can be performed using these data as appropriate to support a partial dose reconstruction.

5.2 SUMMARY OF POTENTIAL INTERNAL RADIONUCLIDE EXPOSURES

Work with radionuclides that created a potential for internal exposure at SNL-CA included limited uranium operations that consisted primarily (but not exclusively) of DU machining and research in the TRL. Radiation workers were monitored using external dosimetry and urine bioassay. A radiation worker was defined as an "employee who received or could potentially receive radiation exposure from his job in excess of 10% of the applicable standards for internal or external exposure" (Wright 1979a). For the purpose of estimating internal dose, individuals working with radioactive materials that present a potential internal exposure were included as radiation workers (Wright 1979a). The numbers of radiation workers based on internal exposure varied over the years. Twenty-one individuals were defined as radiation workers for 1980 based on potential tritium exposure.

5.2.1 Tritium Research Laboratory

The TRL was established in 1976 to perform research and development for the DOE Office of Defense Programs to support weapons development. At its peak of operations, the TRL employed approximately 35 experimenters and support personnel (Garcia and Gorman 1996).

The building was divided into two zones: (1) an office area and (2) a radioactive materials area. The zones were separated by two sets of double doors. The room air in the radioactive materials area was continuously monitored for tritium. The monitoring systems were set to alarm at specific action levels, but there is no indication that the tritium monitoring data were ever used to estimate worker intakes. TRL operations were generally concerned with the physical and chemical characterization of tritium and its compounds. Fabrication of tritium compounds for use as engineering components was also part of the mission of the TRL. All operations involving gram quantities of tritium were conducted inside gloveboxes. The building had a control room where data from the various monitoring devices were stored. This provided for real-time monitoring of facility conditions (Wright 1981a).

Tritium in quantities greater than 0.1 g was doubly contained in gloveboxes, special Sandia-designed containers, or U.S. Department of Transportation-approved containers. The Safety Analysis Report (Wright 1981a) anticipated that 50 g of tritium might be handled in one doubly contained system and that the total tritium inventory in the facility would be approximately 300 g.

Tritium handling operations were terminated in 1992. Cleanup activities were conducted at TRL from January 1992 to December 1995. After 1996, the TRL complex was converted to the CRDL (Garcia and Gorman 1996).

5.2.2 Uranium Alloy Machining

Uranium alloy machining was performed at the SNL-CA facility starting before 1972. Several memoranda indicate that machining and testing of uranium alloys had previously been performed at the Y-12 Plant and elsewhere. However, requirements for SNL-CA were such that they needed "between 50 and 100 specimens of various shapes and sizes per month" (Adolphson 1972), which required initiation of an onsite program.

The radiation safety requirements for the machining operation are described in SOP *Machining Depleted Uranium Metal* (SNL 1989). The DU is designated in the SOP as D-38. The radiation safety requirements included air sampling and urine bioassay (SNL 1989). Daily air samples were required during all machining operations even though air-sampling data had shown that neither wet machining

nor “burning (D-38) chips” (SNL 1989) resulted in airborne particulates. Urine bioassay was required semiannually.

In addition to inhalation exposures, machining of D-38 posed a potential hazard from cuts and splinters. All such incidents were to be reported to the Medical Department and wound counts made on any puncture wounds. No data on wound counts were found in the records available to the authors.

The Uranium Tritide Bed was installed at the TRL in 1991 and also presented a potential for exposure to uranium powder [TRL, SOP No. 757 (SNL 1991a)]. The operating procedure did not specify bioassay requirements. In addition, parts contaminated with UO_2 dust were received by SNL-CA (Lovell 1982) and posed a potential airborne dust hazard.

5.3 BIOASSAY PROGRAMS

Limited bioassay data for tritium and uranium were found from SNL-CA. Tritium exposure occurred primarily in the TRL. However, tritium is ubiquitous in the natural environment as it is a cosmogenic naturally occurring radionuclide and was produced by atomic weapons testing (Turner 1996). Tritium was also present in the environment due to activities at the LLNL facility adjacent to SNL-CA.

The primary detection method for intakes of ^{3}H at all SNL facilities has been urine bioassay (Potter ca. 1997). There is no evidence that urine bioassay samples were analyzed for any radionuclides except ^{3}H and natural uranium, or that other types of bioassay (i.e., fecal analyses or in vivo counting) were employed at SNL-CA. The ^{3}H bioassay was limited to TRL experimenters and staff. The uranium bioassay was performed on individuals who were involved in machining DU as well as others who were involved with handling uranium powders or those in areas where air concentrations potentially exceeded 10% of the air concentration guidelines (Wright 1979a). Records indicate that tritium bioassay was performed at SNL-CA only after the TRL became operational.

5.3.1 Tritium Bioassay Programs

According to Garcia and Gorman (1996), tritium bioassays were performed weekly for individuals who were involved in experimental work at the TRL from 1979 through 1995 when the TRL was decommissioned. Individuals working in the Waste Handling Facility might also have participated in the tritium bioassay program, at least during 1991 (Garcia 1991a, 1991b). Bioassays were also required for all personnel inside the TRL when an evacuation alarm occurred (SNL 1991b). Additional samples were required in some cases by Safe Work Permits (SWPs) or at the discretion of Health Physics.

The *Tritium Research Laboratory Safety Analysis Report* (Wright 1981a) specifies weekly bioassay with samples that were analyzed by liquid scintillation counting (LSC). Laboratory analyses were performed in house by the Health Physics Division. Doses were calculated and reported on a monthly basis.

A 1993 memorandum from Donn Wright to Lydia Perez (Wright 1993) describes the methods by which tritium bioassay data were managed between 1977 and 1993. According to Wright, bioassay results were originally maintained in a VAX text file. The VAX files were transferred into REFLEX, a database program, in 1988. In 1990, the files were sent to SNL-NM for entry into personnel dosimetry histories. As of 1993, the date of the memorandum, the bioassay data were collected by SNL-CA and a hardcopy was sent to SNL-NM monthly or quarterly.

The TRL Health Physics Quarterly Summaries from 1988 through 1995 confirm that urine specimens were collected on a weekly basis and tritium concentrations were determined by LSC. At first,

absorbed doses were calculated for all individuals whose urine bioassay results indicated that they might have received a dose greater than 10 mrem per calendar quarter based on the fact that 10 mrem was the reported sensitivity of the TLDs used for external dosimetry. From 1991 through 1992, absorbed doses were calculated for individuals whose bioassay results indicated a dose greater than 2 mrem per calendar quarter (Garcia 1991b). From 1993 through 1995, absorbed doses were calculated for individuals whose bioassay results indicated a dose greater than 1 mrem per calendar month (Garcia 1993a).

5.3.2 Uranium Bioassay Programs

Uranium bioassays were required for SNL-CA workers who were involved in DU machining and other operations where airborne uranium might have been encountered. The urine bioassay criteria for DU were described in Wright (1979a). The criteria for minimum routine (semi-annual) uranium bioassay were as follows:

- When air sampling results show concentrations at or greater than 10% of the concentration guide of 1×10^{-10} µCi/cm^3;
- For routine handling of uranium hydrides, solutions of uranium compounds, and uranium powders (more than four times per quarter);
- Machining of uranium; and
- During any operation that the Hazards Control Division deemed hazardous or for which an SOP or SWP required air sampling.

Nonroutine bioassays were performed in the following situations:

- Cut or lesion during handling or machining of uranium;
- An individual in close proximity or exposed to a uranium metal fire; and
- Skin contact with a solution of uranium.

DU alloy machining was performed under SOP 1066 (SNL 1989). The SOP required that all machining operations be performed wet, which reduced the risk of fire and generation of airborne dust. Revision C, dated October 1, 1989 (SNL 1989), required semiannual urine bioassay for uranium but noted that “more frequent urine samples are usually collected.”

Air sampling was also required during machining. The machine operators were charged with the responsibility for turning the air samplers on and off. No air concentration data were available to the authors.

5.4 BIOASSAY LABORATORY PROCEDURES AND MINIMUM DETECTABLE INTAKES

The bioassay measurements were performed by various groups during the period of operation of SNL-CA. No specific laboratory procedure manuals were available for either tritium or uranium analyses at SNL-CA.

5.4.1 Tritium

Tritium bioassay was performed at SNL-CA during the entire history of the TRL by LSC.

Revision 3 of the technical basis document (TBD) for internal dosimetry at SNL-CA and SNL-NM states that workers were instructed to fill the entire 1,500 mL urinalysis container (Potter ca. 1997).

However, a single void urine sample was prescribed for tritium. It should be noted that Revision 3 of the TBD was produced after the TRL operations ceased at SNL-CA. (The earliest date for the document would have been 1997 based on the dates of the listed references.)

The frequency and minimum detectable amounts (MDAs) for tritium bioassay from the available quarterly Health Physics Reports and Standard Operating Procedures are given in Table 5-1.

Table 5-1. MDAs for and frequency of tritium bioassay.

Year	MDA	Frequency	Source
1979–1983	Approximately 10 nCi/L (background ±2σ)	Weekly	TRL Health Physics Summary, 1979-1983 (Lovell, Wright, and Hafner 1984)
1980	10 nCi/L,	Weekly	TRL Health Physics Summary, First Quarter 1980 (Hafner 1980)
1980	20 nCi/L	Unknown	Calculated from LSC efficiency and background information in H-3 dose worksheets for 1980
1981	Approximately 10 nCi/L (background ±2σ)	Weekly	TRL Health Physics Summary, First Quarter, 1981 (Wright 1981a)
1986	Approximately 20 nCi/L	Unknown	Calculated based on computer printout for positive exposures for 1986
1988	None given	Weekly	Tritium Research Laboratory Health Physics Quarterly Summaries (October) (Author unknown 1988)
1989	None given	Unknown	Tritium Research Laboratory Health Physics Quarterly Summaries (Author unknown 1989a,b,c,d)
1990	None given	Weekly	Tritium Research Laboratory Health Physics Quarterly Summaries (Garcia 1990a,b,c,d)
1991	None given	Weekly	Tritium Research Laboratory Health Physics Quarterly Summaries (Garcia 1991c,d,e,f)
1991	None given. Reporting limit of 1 µCi/L specified.	Minimum frequency – monthly, but weekly for individuals working primarily in the TRL	SOP No. 709, Tritium Research Laboratory Building 968 (SNL 1991b)
1992	None given	Weekly	Tritium Research Laboratory Health Physics Quarterly Summaries (Garcia 1992a,b,c,d)
1993	None given	Weekly	Tritium Research Laboratory Health Physics Quarterly Summaries (Garcia 1993a,b,c,d)
1994	None given	Weekly	Tritium Research Laboratory Health Physics Quarterly Summaries (Garcia 1994a,b,c,d)
1995	None given	Weekly	Tritium Research Laboratory Health Physics Quarterly Summary for First Quarter (Garcia 1995)
1998	5.5 nCi/L	Unknown	Wright (1998) memorandum to Debbie Miller DOE Albuquerque Special bioassay

According to Hafner (2006), tritium bioassay samples were counted in an LSC under a standard protocol that required a 10-minute count. The volume of urine to be used in any sample was not specified but is assumed to be a minimum of 0.5 mL based on information in available dose calculation forms.

An MDA of 10 nCi/L was reported in the 1980 and 1981 TRL Health Physics Summaries (Hafner 1980; Wright and Hafner 1981). However, a printout of positive exposures for 1986 shows efficiencies between 0.3 and 0.4 and background approximately 20 cpm. While the volume of the

aliquot is not specified, a review of the data in the printout supports the assumption that aliquots of 0.5 mL were used in the analyses. This would lead to an MDC of approximately 20 nCi/L.

Tritium monitoring results were generally reported in dose rather than urine concentration or estimated intake. However, bioassay appointment cards used from April 1982 through October 1982 provided the results of the bioassay and the calculated dose.

The reviewed SNL-CA personnel records generally report calculated dose for tritium rather than urine bioassay data. Chronic Dose Worksheets for 1980 indicate that tritium doses for SNL-CA workers were calculated based on bioassay results as follows:

$$Dose = 0.286\Delta t \ \mu\text{Ci/L} \tag{5-2}$$

The origin of the constant, 0.286, is not defined, and Δt is assumed to be the period of time for which dose is calculated. The dose formula is included here to allow back-calculation of urinary tritium concentrations and tritium intake from dose data.

5.4.2 Uranium

Uranium bioassay samples were sent to SNL-NM for analysis either in house or by a contract laboratory (SNL 1965–1990; Potter 1994). In general, bioassay procedures at SNL-NM required 24-hour urine sample collection. However, urine bioassay questionnaires that were completed by monitored workers at SNL-CA in 1989 and 1990 noted that approximately 50 mL were needed for analysis (SNL 1965–1990). The form contained very brief instructions for sample collection. In contrast, the SNL-NM bioassay kit for 1993 included detailed instructions on how to obtain and deliver the sample (SNL 1993a). Presumably because the uranium bioassays were processed by SNL-NM, the SNL-CA kits would have been the same for that period.

The analyses of uranium bioassays were performed by various laboratories over the course of uranium processes at SNL-CA. For most of the time, the SNL-NM Industrial Hygiene Laboratory performed the uranium bioassay by either fluorimetry or inductively coupled plasma–mass spectrometry (ICP-MS). For several years during the late 1980s, Thermo-Analytical Incorporated/EAL Corporation (TMA/EAL) performed the uranium bioassay. Controls for Environmental Pollution (CEP) performed analyses during the early 1990s (SNL 1993a,b). However, subsequent intercomparison studies indicated that the data from CEP were not reliable. Therefore, dose reconstructors should not use urine bioassay data from CEP analyses in the dose reconstruction. The timeline for uranium bioassays of SNL-CA workers is given in Table 5-2. The information in the table came from individual employee bioassay reports and Wright (1979a).

The results of urine bioassay were generally reported in mass concentration units. There is no information to demonstrate that appreciable amounts of either natural or enriched uranium were used at SNL-CA. Therefore, the dose reconstructor should assume a specific activity for DU when converting mass concentration to activity concentration. The most reasonable specific activity for DU is 4.38×10^{-7} Ci/g as stated by Wright (1979a).

Wright (1979a) states that the minimum detection limit (MDL) by the fluorometric analysis method at SNL-NM was 1×10^{-2} µg/L or 4×10^{-3} µCi/L. These two values are inconsistent, assuming the specific activity of 4.38×10^{-7} Ci/g for DU also stated by Wright. A mass concentration of 1×10^{-2} µg/L would be equivalent to an activity concentration of 4.38×10^{-9} µCi/L. A 1975 analytical report from the Livermore Medical Department shows a detection limit for uranium of 0.005 µg in a 50 mL sample by an unspecified method, which indicates an MDC of 0.1 µg/L (SNL 1975–1977). Other sample data sheets show MDAs of 0.01 µg (SNL 1975–1977). With an aliquot presumed to be approximately 15 mL (the record was nearly unreadable), this would indicate an MDC of approximately 0.7 µg/L.

Table 5-2. Preliminary timeline for uranium in urine analyses.

Period	Laboratory	Method	MDA	Basis and comments
<1968	No information	No information	No information	No information
1968–unknown	Radiation Detection Company (RDC)	Fluorimetry	5 µg/L	Reported error (±2σ)
1973–1986	SNL-NM Industrial Hygiene Services	Fluorimetry Method SAND 75-0014 also reported on the data sheets	Based on lowest reported levels, and the prior MDA, the MDA applicable to this period would most likely be in the range of 5 µg/L	Results reported as 0 in most cases with the lowest reported non-zero values of 1.1 µg/L to 3.2 µg/L appearing occasionally in the records. Retests were requested for positive results
1986	SNL-NM Industrial Hygiene Services	ICP listed as Procedure No.	No information; all results reported as 0	It is unlikely that the method was ICP-MS. It did not come into general use until the early 90s. ICP alone is not sensitive
1986–1987	TMA/EAL	Not specified but probably fluorimetry	"<" values ranged from 3 to 5 µg/L	"<" values provided in the reports
1987–1990	SNL-NM Industrial Hygiene Services	Fluorimetry method SAND88-1149 also referenced	"<" values ranged from 10 to 12 µg/L	Notes on the reports
1990–1993	CEP	No information	No MDC given	Audit memoranda show that CEP analyses were problematic and therefore cannot be used
1993–present	SNL-NM Industrial Hygiene Services	Not defined but probably ICP-MS	0.1 µg/L	Reasonable MDAs for ICP-MS

5.5 BIOASSAY RESULTS

Garcia and Gorman (1996) provide data on doses that were calculated from urine bioassay of TRL experimenters and staff. However, they provide no information on how the urine tritium concentrations or intakes were estimated. For the early years of operation (1979 to 1981) the only data available are the number of workers with doses within specified ranges as shown in Table 5-3.

Table 5-3. Range of tritium doses based on bioassay, 1979 to 1981 (Garcia and Gorman 1996).

Year	Number of workers receiving 10–100 mrem/yr	Number of workers receiving 101–500 mrem/yr
1979	4	1
1980	4	1
1981	6	0

For 1982 through 1995, Garcia and Gorman (1996) show maximum and average doses from intake of ^{3}H at TRL as well as total person-mrem (Table 5-4). The number of monitored workers can be inferred by dividing the total person-mrem by the average dose in millirem.

5.6 METHOD OF CALCULATING DOSE FROM URINE BIOASSAY DATA

In most cases, the information available in the records generally provides only the end result of the calculation; it does not include the actual urine bioassay concentration data. The methods of

Table 5-4. Estimated tritium doses (mrem/yr) based on bioassay, 1982 to 1995 (Garcia and Gorman 1996).

Year	Maximum dose	Average dose	Total person-dose	No. of monitored individuals (inferred)
1982	70	30	183	6
1983	79	49	148	3
1984[a]	1,620	152	3,040	20
1984[b]	234	75	1,420	19
1985	347	65	2,270	35
1986	229	67	1,330	32
1987	178	42	580	14
1988	218	63	1,652	26
1989	232	46	2,465	54
1990	262	30	1,056	35
1991	111	11	458	42
1992	53	11	222	20
1993	63	17	257	15
1994	69	15	190	13
1995	42	15	134	9

a. Maximum individual single event.
b. Maximum, average, and total person-dose excluding maximum individual single event.

calculating doses would have varied over time as more metabolic information and data on retention and urinary excretions of the radionuclides of interest became available.

The reviewed SNL-CA personnel records generally report calculated dose for tritium rather than urine bioassay data. Chronic Dose Worksheets for 1980 indicate that tritium doses for SNL-CA workers were calculated based on bioassay results based on Equation 5-2 above. Again, the origin of the constant, 0.286, is not defined.

5.7 AIRBORNE RADIONUCLIDE CONCENTRATIONS

Work in the TRL was conducted in sealed gloveboxes and/or in gloveboxes used in high-velocity air hood mode. The TRL used two systems for decontaminating glovebox air before release to the environment. The GPS removed tritium from sealed gloveboxes, and the VERS removed tritium from the glovebox pressure control system and the gases exhausted from all of the vacuum pumps in the laboratory. The TRL high-flow ventilation provided 6 to 10 room air changes per hour (SNL 1991b).

Tritium monitors were installed in TRL. The monitors were used to detect the release of tritium into room air, gloveboxes, and the stack as well as to monitor the performance of the GPS and VERS (SNL 1991b). The monitors activated audible and visible alarms at the monitoring point and in the TRL control room. At least one operating tritium monitor was required in each room.

According to the quarterly reports, the tritium monitoring system was continually upgraded from 1988 through 1995. A planned new tritium monitoring system was cancelled in 1992 (Garcia 1992a). Monitors were installed in the hallways of the TRL. Double monitoring was conducted in each laboratory. As of 1988, 60 tritium monitors were in use (Author unknown 1989a,b,c,d).

The tritium monitors had Room Air Low and Room Air High alarms. The Room Air Low alarm was triggered at a concentration of 30 µCi/m^3. The Room Air High alarm was set at 1 mCi/m^3. The maximum permissible concentration in air and the more recent derived air concentration (DAC) remained constant at 2×10^{-5} µCi/mL (20 µCi/m^3) throughout the operational history of the TRL. The alarms were checked on a routine basis. If a Room Air Low alarm was triggered, workers were

required to mitigate the release within a few minutes and exit the room if the air concentrations did not decrease. A Room Air High alarm required evacuation from the room within 1 minute (SNL 1991b).

Airborne uranium dust concentrations were measured in the areas where DU was machined. No data on measured concentrations or action levels were available to the authors.

5.8 UNMONITORED DOSE ESTIMATES

The vast majority of SNL-CA workers were employed in areas with little or no potential for intake of radionuclides that were generated at their work areas (Wright 1979b; Bryson 1972). Therefore, only a small proportion of workers were required to participate in the bioassay program. Individuals who worked in the laboratory areas as experimenters or support personnel could have been exposed to airborne tritium (SNL 1991a,b). Machinists and others who worked in areas where DU was machined or other uranium operations were conducted could have been exposed to airborne uranium dust (SNL 1989).

For years after 1994, if no bioassay records are available for claimants who are on record as having worked in the TRL or uranium machining areas, potential unmonitored doses or intakes can be calculated based on 10% of the airborne radionuclide concentrations limits because the procedures required monitoring for individuals who could have potentially received internal doses in excess of 10% of the dose limit (Wright 1993) or when air sampling results demonstrated that air concentrations could reach or exceed 10% of the concentration guides for air (Wright 1979b). The applicable DAC values in place at the time in air are given in Table 5-5.

Table 5-5. DAC values (µCi/mL) for tritium and uranium (DOE 1993, Appendix A).

Period	HTO[a]	U-238[b] type F	U-238[b] type M	U-238[b] type S
After 1994	2E−5	6E−10	3E−10	2E−11

a. Assigned through 1996, environmental intakes assigned thereafter.
b. Assigned through 1998, environmental intakes assigned thereafter.

The calculated annual intake for an unmonitored worker inhaling tritium at 10% of a DAC or 2×10^{-6} µCi/mL, assuming a breathing rate of 1.2 m^3/hr for 2,000 hr/yr, would be 4.8×10^3 µCi. After an adjustment of 1.5 for skin absorption, the intake would become 7.2×10^3 µCi. This would be applicable for 1995 and 1996 only, because decommissioning of the TRL was completed in 1996. After 1996, environmental intakes should be assigned.

The calculated annual intakes for an unmonitored worker inhaling uranium at 10% of a DAC would be 6×10^{-11} µCi for type F uranium, 3×10^{-11} µCi for type M uranium, and 2×10^{-12} µCi for type S uranium. These intakes would be applicable for 1995 to 1998. After 1998, environmental intakes should be assigned.

Because SNL-CA is close to LLNL, it is not the only source of airborne radionuclides. Intakes for workers outside those facilities can, if necessary, be calculated based on environmental air concentrations.

5.9 RADIATION DOSIMETRY REPORTS

The AEC required annual dose report summaries for workers (Burke 1969). Records of annual dose reports for 1958 through 1967 were reviewed. The reports from 1964 through 1968 and from 1973 showed no internal body depositions or exposure to airborne materials that resulted in internal body deposition as determined by bioassays. The reports for 1962 and 1963 specified no internal depositions in excess of one-half the body burden. Between 1958 and 1962, the reports state that

there were no exposures resulting in internal body deposition of radioactive materials. The reporting form changed in 1976; subsequent reports for 1977 and 1978 did not show internal exposures.

The Personnel Monitoring and Laboratory Services department at SNL-NM issues monthly ALARA Radiation Dosimetry Reports that list all employees whose annual dose equivalent exceeds specific action levels of 2%, 6%, and 10% of the applicable 10 CFR Part 835 limiting values (SNL 1997). The reports include external doses as measured by TLD badges and internal doses as committed effective dose equivalent (CEDE). The column for CEDE remained blank in most cases, presumably where no bioassays were performed. It is not clear whether these reports included SNL-CA employees.

Before 1973, external doses were documented by SNL-CA. Tritium doses acquired at sites other than SNL were noted occasionally in the records (SNL undated c). The notation showed values less than 3 µCi/L (presumably in urine). One record in this undated document showed "3 MC/L," but the entries in this record were all in capital letters, and it was most likely meant to be 3 µCi/L.

Termination Occupational Exposure Reports were also filed for SNL-CA employees. These reports were primarily focused on external exposures but did include a section for internal exposure (SNL 1980–1984).

5.10 SUMMARY TABLES

Tables 5-6 to 5-9 incorporate the best general information available about MDAs. However, it should be noted that some individual data in the reviewed records showed lower MDAs or reported urine bioassay values less than the listed MDA.

Table 5-6. Internal dose control program.

Routine monitoring type	Period	Frequency
Urine – tritium	1977–1995	Weekly
Urine – uranium	1968–present	Semiannual or as required by the Hazards Control Department

Table 5-7. Detection limits for urine bioassay for ^{3}H with LSC.[a]

Period	MDA (pCi/L)
1977–1983	10,000 (reported)
1980–1985	20,000 (calculated for 1980 based on background and efficiency for the LSC)
1986	20,000 (calculated)
1986–1997	10,000 (estimated based on previous reported MDAs)
1998–present	5,500

a. Reporting limits were based on dose rather than bioassay results.

Table 5-8. Detection limits for total uranium bioassay.[a]

Method	Period	MDA (µg/L)[b]
No data	Before 1968	5 (based on state of technology)[c]
Fluorimetry	1968	5 (based on reported error)
Fluorimetry	1969–1973	5 (estimated based on 1968 data)
Fluorimetry	1973–1986	5 (individual employee bioassay reports as low as 0.7)
Fluorimetry	1986–1987	3
Fluorimetry	1987–1990	10
CEP	1991–1992	Audit memoranda show that CEP analyses were problematic and thus cannot be used.
ICP-MS	1993–present	0.1

a. No reporting limits were available in the documents provided to the authors.
b. Dose reconstructors should use the MDA data provided in the bioassay records when available.
c. MDA of 5 µg/L is consistent with the value reported for bioassay conducted at nearby LLNL site (ORAUT 2016) and the Hanford Site (ORAUT 2015).

Table 5-9. Facility, source, solubility type, and particle size.

Facility	Source	Solubility type	Particle size
TRL (Building 968)	H-3	Tritiated water	Not applicable
Building 913 Machine Shop	DU	Metallic form – unspecified solubility type but likely Type S	No data
Building 968	Uranium tritide	Type F[a]	No data
Building 913	UO_2	Type S	No data

a. Described in Section 3.0 of ORAUT (2007b).

6.0 OCCUPATIONAL EXTERNAL DOSE

6.1 INTRODUCTION

6.1.1 Purpose

The purpose of this section is to detail historical external dosimetry programs, systems, and practices at SNL-CA. This information may be used by dose reconstructors as needed to evaluate external occupational doses for EEOICPA claimants in terms of supplementing individual dose records for monitored SNL-CA workers, estimating respective missed doses, or estimating doses for unmonitored workers.

6.1.2 Scope

Historical documentation about radiological protection programs at SNL-CA indicates that external dosimetry monitoring for workers and visitors at SNL-CA has been performed throughout the site's history. The information in this section draws on review of currently available records. The review for years before 1991 contains less information due to fewer available supporting documents. In the event further relevant documents are found for any period during the site's history, this section will be revised accordingly.

6.1.3 Special Exposure Cohort

NIOSH has determined that it is not feasible to estimate with sufficient accuracy beta, gamma, and neutron external exposures from October 1, 1957, through December 31, 1994, resulting from HEU, uranium hydrides, Radiography Facility isotope sources, thorium, classified work, and resulting doses for the class of employees covered by this evaluation (NIOSH 2013). Therefore, this period has been included in the SEC. Dose reconstruction guidance in this document for this period is presented to provide a technical basis for partial dose reconstructions for nonpresumptive cancers not covered in the SEC class or for claims with less than 250 working days in the SEC period.

Although NIOSH found that it is not possible to completely reconstruct external radiation doses for the designated class, it intends to use any external monitoring data that might become available for an individual claim (and that can be interpreted using existing NIOSH dose reconstruction processes or procedures). Therefore, for individuals employed at SNL-CA from October 1, 1957, through December 31, 1994, who do not qualify for inclusion in the SEC, dose reconstructions can be performed using these data as appropriate to support a partial dose reconstruction.

6.2 BACKGROUND

Historically, tritium exposure has been the primary radiological concern at SNL-CA (Ullrich 2003; DOE 2006). However, tritium exposure is not significant in terms of external dose. As noted in Section 2.2, the laboratory typically handled kilogram amounts of DU (typically in the form of alloyed metal components), gram amounts of ^{3}H, and microcurie quantities of other isotopes. The Radiography Facility (Building 923) also contained 100-Ci ^{192}Ir and ^{60}Co sources, a sealed ^{252}Cf source, and many

other smaller sealed sources of activity ranging from 500 mCi to 1 Ci (see Section 2.3). According to a DOE website, uranium exposure potential at SNL-CA is extremely small and there is no potential for plutonium exposure (DOE 2006). Radioactive waste at SNL-CA is categorized as low level. High-level or transuranic waste is not generated or stored at SNL-CA (SNL 1992). Table 2-1 summarizes the SNL-CA buildings of potential radiological interest.

LLNL performed external film dosimetry monitoring services for SNL-CA from 1956 to 1959 (SNL 1958–1961). After that, a commercial vendor, Radiation Detection Company (RDC), provided film dosimetry services until the early 1970s (SNL 1958–1961, 1961–1962, 1962; DeSelm 1965; SNL 1964; Lovell 1966; RDC 1969). In 1962, there was a brief transfer of contracted film processing services from RDC to a similar provider called Tracerlab (SNL 1962), but Tracerlab was quickly dropped due to poor performance and the contract with RDC was reestablished. From about 1972 to 1988, SNL-CA external dosimetry was outsourced to the DOE Radiological and Environmental Sciences Laboratory (RESL) in Idaho Falls, Idaho (Wright 1993, Wallace 1988, Ormond 1986). In 1989, dosimetry services for SNL-CA were transferred to SNL headquarters in Albuquerque, New Mexico (SNL-NM).

In 1991, the dosimetry processing laboratory at SNL-NM became accredited under the DOE Laboratory Accreditation Program (DOELAP) (Loesch 1991) as part of the overall plan to provide centralized, unified, and permanent dosimetry services for SNL-CA and other Sandia sites (Stanley 1991; SNL 1992; Ward 1994). Most of the dosimetry information presented, described, and evaluated in this section for years after 1991 was obtained at SNL-NM by the Oak Ridge Associated Universities (ORAU) Team for the purpose of developing a site profile for that site (those records are directly applicable to the dosimetry program at SNL-CA from 1991 forward). Although the currently available records do not fully describe many technical details of dosimetry programs before DOELAP accreditation in 1991, they do provide an indication of the types of dosimeters that were used, exchange periods, and in most cases, types of radiation dose quantities that were measured and recorded.

6.3 DOSE RECONSTRUCTION PARAMETERS

6.3.1 Site Historical Administrative Practices

6.3.1.1 Administrative Practices Before 1989

Documents from early in the SNL-CA site history indicate a policy of maintaining permanent dosimetry records (SNL 1963). Between 1956 and 1959, most SNL-CA employees, contractors, and visitors were required to wear dosimeter badges (SNL 1958–1961, 1958–1978). During this time, LLNL was performing dosimetry services for SNL-CA, and records management was implemented manually by SNL-CA personnel. Records management continued to be administered by SNL-CA (Division 8242-2) for the subsequent period in which RDC provided dosimetry services (1959 to about 1971). By 1965, discussions among SNL-NM management were taking place about the need to badge all personnel on the site versus badging only personnel with access to “exclusion zones” (areas where radiation fields were present). Over time, the policy of badging all personnel was abandoned in favor of badging only individuals with potential to exceed certain exposure limits, which appears to have occurred in 1970 according to summarized annual reports of external exposures (SNL 1958–1978). Through about 1972, dosimetry results were recorded manually on 4- by 6-in. cards or were stored as text file hardcopies, all of which were transferred to SNL-NM in 1993 (Wright 1993). Electronic external dosimetry records for 1973 to 1988 were transferred to SNL-NM in 1989 (Wright 1993) and apparently became part of a master electronic records database management program called SANDOS. Since 1989, dosimetry records for all Sandia sites have been retained and managed by SNL-NM (Ward 1994).

6.3.1.2 Administrative Practices After 1989

In 1989, the dosimetry program at SNL-CA was transferred to SNL-NM and has since been directed and managed by SNL-NM Personnel Dosimetry Department 7715; onsite oversight and implementation was conducted by SNL-CA Personnel Dosimetry Department 8541 (Ward 1994). Dosimetry records from Department 7715 are entered into SANDOS. An example personnel dose history output (SNL 1993c) is shown in Attachment B (Figure B-1). Although dose units are not stated in SANDOS output, review of other documents (SNL 1993c) suggests that they are reported in rem. There are specific protocols and required training for dosimetry data entry and records management (Ward 1994).

Consistent with DOE Order 5480.11, Section 9.g (DOE 1988), administrative external dose limits for SNL-CA personnel are as follows:

- 100 mrem (0.001 sievert) annual effective whole-body dose equivalent;
- 5 rem (0.05 sievert) annual dose equivalent to the skin;
- 5 rem (0.05 sievert) annual dose equivalent to any extremity; and
- 1.5 rem (0.015 sievert) annual dose equivalent to the lens of the eye.

Any site personnel with potential to receive annual doses exceeding these limits are required to wear personal dosimeters (Thompson 1991; Ward 1994). Monitored workers with interim dosimetry results indicating that annual doses could approach or exceed these limits can have work restrictions imposed. A 1997 memorandum announced an apparent change in dose limit reporting protocols under the SNL ALARA policy (Figure 6-1; SNL 1997). These limits are similar to those listed above, but it is unclear whether they represent a combined total of both internal and external doses.

Attached are the monthly ALARA Radiation Dosimetry Reports. The reports list the occupational radiation dosimetry records for those employees whose annual dose equivalent exceeds 2, 6, and 10 percent of the limiting values specified in 10 CFR 835, Occupational Radiation Protection.

When an employee's annual dose equivalent exceeds the ALARA Report action levels, the individual's records will appear on subsequent monthly reports until the end of the current year. 10 CFR 835 limiting values and the ALARA Report action levels are given in the following table.

ORGAN	10 CFR 835 LIMITING VALUES (rem)	ALARA REPORT ACTION LEVELS (rem)		
		2%	6%	10%
Whole Body	5.0	0.1	0.3	0.5
Skin	50.0	1.0	3.0	5.0
Extremity	50.0	1.0	3.0	5.0
Lens of Eye	15.0	0.3	0.9	1.5

Figure 6-1. ALARA reporting action levels (SNL 1997).

There are two dosimeter categories for monitoring personnel on the site: routine field dosimeters and nonroutine field dosimeters. Routine field dosimeters are required (as specified above) for regular employees or contractors working at the site for extended periods, and results are reported on a quarterly basis. Nonroutine field dosimeters are issued to short-term temporary workers, site visitors,

or personnel performing special radiation work outside the scope of their normal activities (i.e., nonroutine work tasks where the potential for additional or special types of exposures might exist).

While not made explicitly clear in Section 8.4.1 of the SNL External Dosimetry Program Manual (Ward 1994), routine field dosimeter exchanges appear to occur on a monthly or quarterly basis while nonroutine exchanges occur on a biweekly basis (for special radiation work cases, exchange periods can vary).

Before doses are calculated from gross field TLD readings, the amount of measured thermoluminescence due to background radiation is subtracted to obtain a net result due only to radiation from occupational exposure (Bradley et al. 1994, 1995; Walker 1996). Background thermoluminescence is the summation of "system background" and "environmental background." System background consists of thermoluminescence inherent in the instrumentation (e.g., noise due to photomultiplier tubes) and is determined from reread values for daily measurements of calibration cards. Environmental background consists of accumulated exposures from cosmic and terrestrial background sources and is determined from trip control dosimeters that accompany each batch of field dosimeters to and from each SNL site. In addition to monitoring exposures during shipping, trip control dosimeters remain stored at daily check-in and checkout locations while at a given SNL site so that only site-specific background radiation is accumulated. The locations of badge storage areas for SNL-CA have not been identified.

Routine field dosimeters are assigned and issued by department managers and are subject to specific protocols for onsite use as well as for subsequent handling and shipment to the Personnel Dosimetry Division in the New Mexico office for processing. Personnel who are issued routine field dosimeters are required to have documented training on dosimeter use as well as general radiation safety training.

Dosimeter shipping and handling quality control protocols include the use of special zippered envelopes for transport, dosimeter issue and return lists, chain-of-custody control documentation, trip control cards, and express (overnight) shipping, and upon arrival at the NM Processing Center all field dosimeters are inspected for physical damage and card assignments are verified (Ward 1994).

Nonroutine field dosimeters for temporary employees and visitors are issued by the Security Patrol Division at specified site check-in locations. The Security Inspector is responsible for ensuring proper documentation of personnel being issued nonroutine field dosimeters and for instruction in their use while on the site. With the apparent exception of dosimeter exchange periods, protocols for nonroutine field dosimeter handling and shipment to the NM Processing Center are the same as those for routine field dosimeters.

Nonroutine field dosimeters for special radiation work cases are requested from Division 7715 and issued by department managers for personnel who are involved in such work (Walker 1995). Respective examples of reporting for this type of nonroutine evaluation are provided in Attachment B (Figures B-2 and B-3).

Dosimetry results greater than 1 rem, questionable results, suspected misuse, processing difficulties, and unreturned field dosimeters result in a formal investigation to resolve the issue as well as to document and justify the dose equivalent assigned to the individual's dosimetry record. Radiation work restrictions can be imposed pending resolution of an investigation. Example documentation of an unreturned dosimeter investigation and assignment of missed dose are provided in Attachment B (Figures B-4 to B-6).

The overall performance of the SNL Personnel Radiation Dosimetry Program is monitored quarterly by a blind audit (Ward 1994), but who performs these audits is unclear.

In addition to personnel radiation dosimetry, SNL-CA conducts a Special Dosimetry Program that includes work area monitoring (Ward 1992; SNL 1995). These dosimeters are also considered "nonroutine" and respective exchange periods can vary depending on the intended monitoring purpose. An example request form and results report for work area dosimeters are provided in Attachment B (Figures B-7 and B-8). Shipping and handling procedures are identical to those for personnel field dosimeters and the dose equivalent results are also recorded in SANDOS (SNL 1995).

6.3.2 Site Dosimetry Technology

The historical progression of dosimeter technologies for external dose monitoring at SNL-CA is shown in Table 6-1. As broken down and discussed in the following sections, site dosimetry technologies have been partitioned into two historical timeframes (1956 to 1988 and 1989 to the present). This is because, for dose reconstruction, more complete and detailed information is available from after 1989 to describe the dosimetry program after 1989.

Table 6-1. Documented dosimetry technologies and dose quantities (SNL 1958–1961, 1958–1978, 1962, 1963, 1964; Wright 1993).

Dosimeter type	Years	Dosimetry service provider	Measured quantities	Exchange frequency	Compliance dose quantities
Two-element beta/photon film + NTA neutron film	1956–1959	LLNL	Photons, beta, neutron, penetrating, nonpenetrating	Monthly	AEC Manual chapter 0524
Two-element beta/photon film + NTA neutron film	1959–1971	RDC	Photons, beta, neutron, penetrating, nonpenetrating	Monthly	AEC Manual chapter 0524
2-chip TLD (one filter type only)	1972–1982	RESL	No discrimination of different radiations. Photons, beta, neutron, penetrating, nonpenetrating	Semiannual	AEC Manual chapter 0524
3-element Eberline TLD	1982–1988	RESL	Photons, beta, neutron, penetrating, nonpenetrating	Annual or semiannual	ANSI N13/WD-2 (N324) 1978 penetrating/ nonpenetrating, photons: <0.3 MeV, 0.3–10MeV, betas: 0.2–2.0MeV, photon/beta mixtures
Multielement Harshaw TLD (separate special dosimeter for neutrons)	1989–1990	SNL-NM	Shallow (Sh), deep (Dp), neutron (Nt)	Quarterly	Skin = Sh + Dp + Nt WB = Dp + Nt, extremities = Sh + Dp + Nt
Multielement Harshaw TLD	1991–present	SNL-NM (DOELAP)	Shallow (Sh), deep (Dp), neutron (Nt)	Quarterly	Skin = Sh + Dp + Nt WB = Dp + Nt, extremities = Sh + Dp + Nt

6.3.2.1 Dosimetry Technology, 1956 to 1988

As suggested by some of the documents Table 6-1 cites, dosimeters that were worn by SNL-CA personnel between 1956 and the early 1970s consisted of two-element DuPont Type 554 beta/photon film along with nuclear track emulsion, type A (NTA) film. Film badges consisted of four windows with one open and the others filtered with various densities of lead, cadmium, and aluminum (RDC 1963). There is a discrepancy in the available record as to exactly when SNL-CA discontinued using film dosimeters and began using TLDs. *Dosimetry History 1993* (Wright 1993) indicates that this switch occurred in about 1966. Lovell (1966) indicates continued use of film in 1966, with plans to continue

that use. Lovell (1983) estimates the use of TLDs began in about 1968. RDC (1969) indicates that they were still processing badges for SNL-CA as late as 1970, but it is not clear whether TLD technology was in use at the time. It is possible that the switch to TLDs coincided with a switch of dosimetry service providers from RDC to RESL in Idaho Falls, Idaho (Wright 1993), or that there was some overlap in use of film and TLDs. Due to the uncertainty, it is favorable to the claimant, in cases where missed dose is estimated, to assume that film dosimeters were used at SNL-CA until about 1972.

As reported in Wright (1993), up until 1982 the SNL-CA TLD technology consisted of a two-chip badge with only one filter type [30 mg/cm^2 total filtration according to Wright (1981b)] and as such, it could not discriminate between different radiation types or energies. However, the actual dosimetry records for this period report both penetrating and nonpenetrating doses including beta, photon, and neutron radiations. If the TLDs during this period could not directly measure these different dose quantities, it is not clear if (or how) adjustments to recorded dose were made. Wright (1981b)

suggests that nonpenetrating dose could have also been assigned as penetrating dose, but the document does not provide any indication of how different radiations, including neutron doses, were assessed. In 1982, SNL-CA switched to a three-element TLD from Eberline that apparently could better discriminate between different radiation types and provide directly measurable indicators of these various dose quantities. SNL-CA continued using the Eberline dosimeter until about 1989.

6.3.2.2 Dosimetry Technology, 1989 to Present

Since 1989, radiation dose monitoring at SNL-CA has been based primarily on the use of Harshaw TLDs. The Harshaw 8800 series TLD systems were the first to be DOELAP accredited at SNL and are the predominant systems used at all Sandia sites. Harshaw 4000 series TLDs are apparently used as well (Tucker 1977a,b, 1978; Kay 1979; Stanley 1987a,b,c; SNL 1996a), but little information is currently available on the specific application and extent of use of this series. There is some evidence that the 4000 series might have been used, at least until 1996, for extremity dose monitoring (Walker 1997a). In 1997, SNL began using Harshaw/Bicron EXTRAD dosimeters for extremity monitoring. There is some indication that, in addition to routine dosimeters for regular workers in the Radiography Facility, pocket dosimeters were used for nonroutine personnel accessing that facility (Lovell 1984a, 1984b).

Because the Harshaw 8800 system is a primary method for external personnel dosimetry monitoring at SNL-CA, it is pertinent to describe some of its basic technologies. Model 8801 and 8802 TLD cards consist of four thermoluminescence elements between two thin sheets of Teflon, all of which is sandwiched between aluminum jackets. The jackets have four holes positioned over the thermoluminescence elements so they can be heated by hot N_2 gas in the card reader. For operational efficiency, SNL color-codes TLD card edges according to use (e.g., calibration cards have green edges, quality control cards have red edges, and field cards for worker monitoring have no added coloring).

The assembled dosimeter consists of the TLD card inside a Model 8812 cardholder. The cardholder front has radiation-modifying filters to evaluate radiation and dose equivalent quantities as shown in Figure 6-2. For simplicity, the manufacturer refers to the entire assembly as a Model 8812 dosimeter, while SNL refers to this assembly as the SNL dosimeter.

The Harshaw 8800 card reader is an automated system in which up to 1,400 cards can be loaded at a time and read automatically. Barcode identification information on each card is automatically recorded by the card reader before heating. Precisely controlled heating causes the TLD elements to give off light in proportion to the amount of radiation they have received. The light is converted to an electrical signal by a photomultiplier tube. The relative strength of the electrical signal is measured in

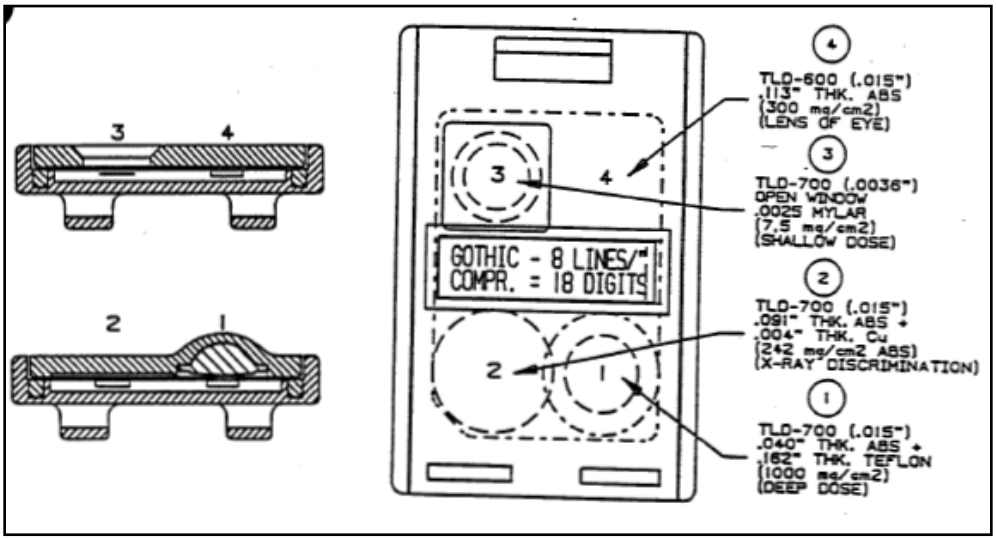


Figure 6-2. Harshaw Model 8812 dosimeter assembly, element specifications, and respective radiation and dose equivalent quantities measured by Rhea and Bradley (1990).

units of charge (nanocoulombs) to create glow curves that are then analyzed against card reader calibration parameters. Noncontact heating of the cards with hot nitrogen gas improves dosimeter reuse, durability, and improves glow-curve reproducibility. Raw data from the card reader is acquired, analyzed, and stored with TLD Radiation Evaluation and Management System software on a desktop computer. Card reader results are converted into dose equivalents by a complex algorithm that was developed specifically for the Harshaw 8800/8812 system and SNL sites.

Along with explicit protocols for card reader calibration, accredited DOELAP programs involve an ongoing process that includes repeated algorithm validation and blind audits as part of an overall data quality assurance program. Calibration and algorithm protocols are described in more detail in subsequent sections.

6.3.3 Calibration

6.3.3.1 Calibration for Dosimeter Technologies, 1965 to 1988

Calibrations for film dosimeters processed by RDC in the 1960s involved exposing film in SNL-CA badges to known ^{60}Co gamma and X-ray fields (effective X-ray energies were 35 keV and 90 keV) based on previous calibration data for RDC badges (RDC 1963). SNL-CA badges had aluminum, cadmium, and lead filters, each of which was cross calibrated against similarly filtered RDC badges in parallel runs. Calibration of TLD badges SNL-CA used between 1971 and 1988, the period in which RESL performed dosimetry services, are provided as follows.

- Cesium-137 was considered for a calibration source in 1959 (AEC 1960, p. 83) and was installed in the instrument calibration facility in 1961 (Horan 1962). An automatic badge irradiator developed in the 1960s did not use a phantom to provide backscatter (Cipperley 1966).

- As reported in 1981, an extrapolation chamber was built for the measurement of beta doses (Gupta 1981). The chamber window was polycarbonate, the gas was air, and the thick collecting electrode was Shonka tissue-equivalent plastic. The chamber was used to calibrate a 2.5-Ci ^{90}Sr/Y source to tissue rad. The source, with an area of 2.5 cm^2, was constructed by the Amersham Searle Corporation in February 1975. This source was used to measure beta

correction factors for several instruments after the Three Mile Island-2 reactor accident in 1978. TLD badges were calibrated to 500 mrad tissue using a 1.78-cm-thick phantom 50 cm from the source (300 rad/hr).

- In January 1983, the natural uranium slab again became the primary calibration source for nonpenetrating radiation to better approximate field beta spectra (Gesell 1982).

- Use of a phantom in calibration apparently started in 1981 with the National Voluntary Laboratory Accreditation Program (NVLAP) certification process developed for non-DOE dosimetry processors. About this time, calibration developed in terms of absorbed dose to tissue rather than exposure. Beginning in January 1981, in response to a draft NVLAP (a precursor for DOELAP) standard, dosimeters for calibration were irradiated with ^{137}Cs using a phantom backing. To convert from exposure in roentgen to dose equivalent index in rem, a conversion factor *Cx* value of 1.08 was used (DOE 1981). The current recommended *Cx* value of 1.03 for ^{137}Cs (DOE 1986a, Table 2) was used beginning in June 1981 (Gesell 1982b; Kalbeitzer 1984).

6.3.3.2 Calibration for Dosimeter Technologies, 1989 to Present

Harshaw Model 8800 TLD card readers are set up and maintained in accordance with manufacturer recommendations. Figure 6-3 shows a calibration procedure flowchart (Bradley et al. 1995) along with an example calibration checklist, glow curves, and calibration results output (SNL 1996b).

Specific details of the Harshaw 8800/8812 system calibration procedures can be found in Bradley et al. (1993) and Rhea and Bradley (1990). Procedures appear to be different for calibration of the Harshaw 4000 system (SNL 1996a), and an example calibration form is shown in Figure 6-4. No official manuals or procedural documents have been found about the Harshaw 4000 dosimetry system calibration or system applications, and no similar documentation has been found about the Harshaw/Bicron EXTRAD system.

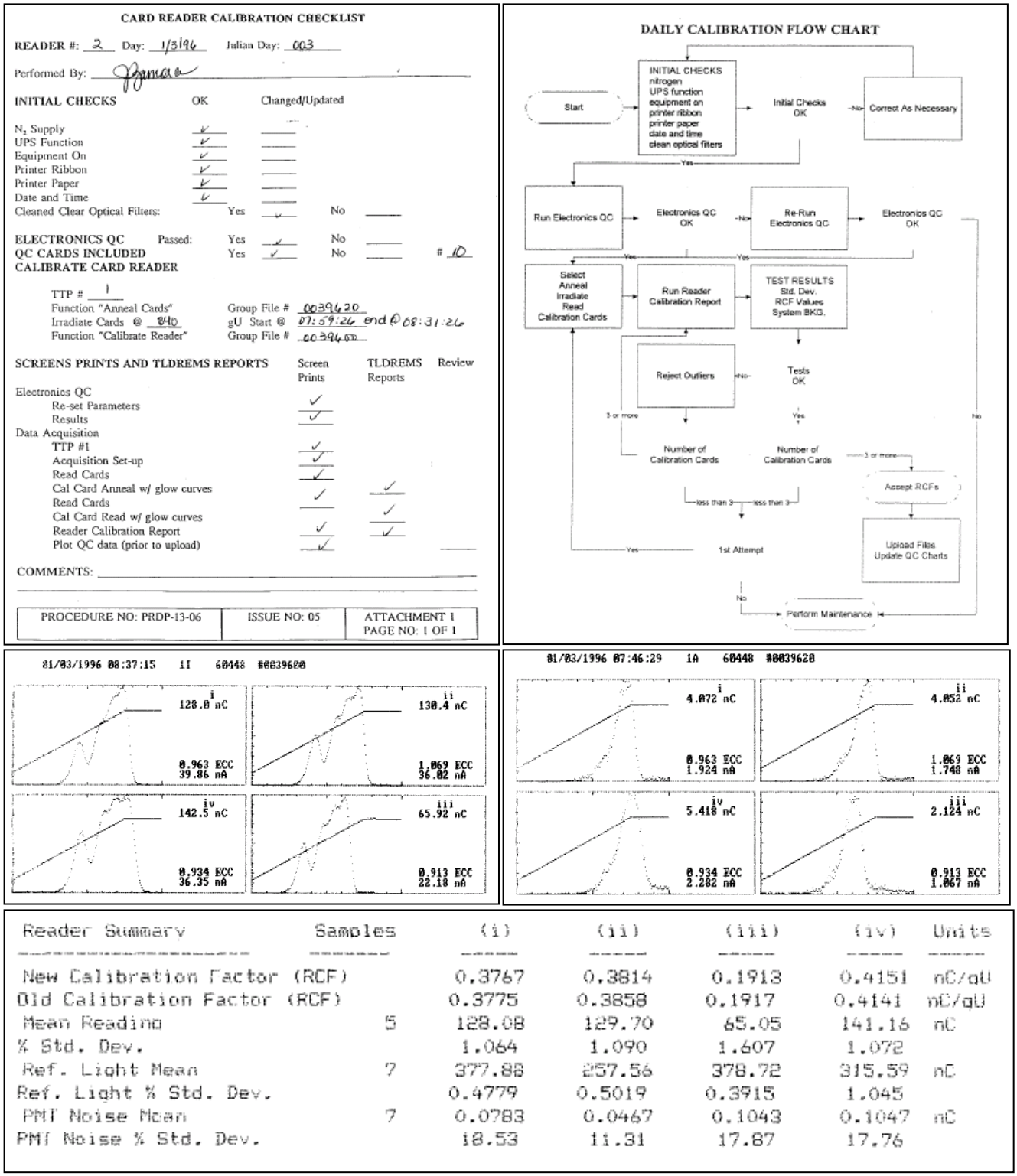
6.4 DOSE CALCULATION AND REPORTING

6.4.1 Dose Calculation and Reporting, 1956 to 1988

As shown in Table 6-1, reported doses for SNL-CA employees, contractors, and visitors through 1988 include penetrating and nonpenetrating categories for beta, photon, and neutron radiations. For the period in which film was used for measuring these quantities, it is assumed that the degree of film darkening under the various windows (filtered to different degrees) was used to estimate doses within these reporting categories by comparison against calibration curves that were developed for each batch of film. No information is currently available about MDLs, uncertainty or bias, or adjustments to recorded dose during this period of film dosimeter use.

As mentioned previously, the two-chip single-filter TLD dosimeters in use from about 1972 to 1982 apparently could not directly measure each of the various dose quantities that were reported in the record for this period. No definitive information has been found about adjustments to recorded dose, and no information has been found about dose calculation algorithms, system MDLs, or uncertainty or bias during this period.

Like the earlier period in which two-chip TLDs were used at SNL-CA and processed by RESL in Idaho, there is no documentation about dose calculation algorithms, MDLs, adjustments to recorded dose, or uncertainty or bias for the three-element Eberline TLD badges that were used from 1982 to 1988.



CARD READER CALIBRATION CHECKLIST

READER #: 2 Day: 1/3/96 Julian Day: 003

Performed By: Jgmcan

INITIAL CHECKS	OK	Changed/Updated
N_2 Supply	✓	
UPS Function	✓	
Equipment On	✓	
Printer Ribbon	✓	
Printer Paper	✓	
Date and Time	✓	
Cleaned Clear Optical Filters:	Yes ✓	No

ELECTRONICS QC Passed: Yes ✓ No
QC CARDS INCLUDED Yes ✓ No # 10
CALIBRATE CARD READER

TTP # 1
Function "Anneal Cards" Group File # 0039620
Irradiate Cards @ 840 gU Start @ 07:59:26 end @ 08:31:26
Function "Calibrate Reader" Group File # 0039600

SCREENS PRINTS AND TLDREMS REPORTS	Screen Prints	TLDREMS Reports	Review
Electronics QC			
Re-set Parameters	✓		
Results	✓		
Data Acquisition			
TTP #1	✓		
Acquisition Set-up	✓		
Read Cards	✓		
Cal Card Anneal w/ glow curves	✓	✓	
Read Cards			
Cal Card Read w/ glow curves		✓	
Reader Calibration Report	✓	✓	
Plot QC data (prior to upload)	✓		

COMMENTS:

PROCEDURE NO: PRDP-13-06	ISSUE NO: 05	ATTACHMENT 1 PAGE NO: 1 OF 1

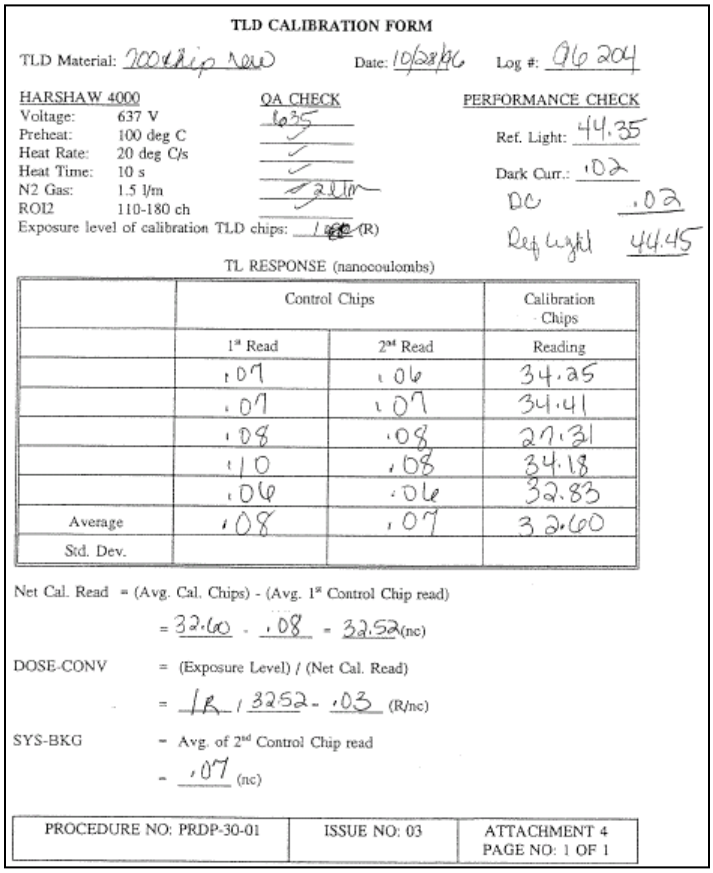
DAILY CALIBRATION FLOW CHART

Reader Summary	Samples	(i)	(ii)	(iii)	(iv)	Units
New Calibration Factor (RCF)		0.3767	0.3814	0.1913	0.4151	nC/gU
Old Calibration Factor (RCF)		0.3775	0.3858	0.1917	0.4141	nC/gU
Mean Reading	5	128.08	129.70	65.05	141.16	nC
% Std. Dev.		1.064	1.090	1.607	1.072	
Ref. Light Mean	7	377.88	257.56	378.72	315.59	nC
Ref. Light % Std. Dev.		0.4779	0.5019	0.3915	1.045	
PMT Noise Mean	7	0.0783	0.0467	0.1043	0.1047	nC
PMT Noise % Std. Dev.		18.53	11.31	17.87	17.76	

Figure 6-3. Example Harshaw 8800 card reader calibration procedures, forms, analysis, and output.

6.4.2 Dose Calculation and Reporting, 1989 to Present

The algorithms SNL used for calculating dose equivalents are specific to each particular dosimeter system (Bradley et al. 1994). Both shallow (0.007 cm) and deep (1.0 cm) dose equivalents are measured, calculated, and reported. Although dose to the lens of the eye is not measured directly, it



TLD CALIBRATION FORM

TLD Material: 200 chip new Date: 10/28/96 Log #: 96 204

HARSHAW 4000
Voltage: 637 V
Preheat: 100 deg C
Heat Rate: 20 deg C/s
Heat Time: 10 s
N2 Gas: 1.5 l/m
ROI2 110-180 ch
Exposure level of calibration TLD chips: 1 (R)

QA CHECK
635
✓
✓
✓
22 In
✓

PERFORMANCE CHECK
Ref. Light: 44.35
Dark Curr.: .02
DC .02
Ref Light 44.45

TL RESPONSE (nanocoulombs)

	Control Chips		Calibration Chips
	1st Read	2nd Read	Reading
	.09	.06	34.25
	.07	.07	34.41
	.08	.08	27.31
	.10	.08	34.18
	.06	.06	32.83
Average	.08	.07	32.60
Std. Dev.			

Net Cal. Read = (Avg. Cal. Chips) - (Avg. 1st Control Chip read)
= 32.60 - .08 = 32.52(nc)

DOSE-CONV = (Exposure Level) / (Net Cal. Read)
= 1R / 3252 - .03 (R/nc)

SYS-BKG = Avg. of 2nd Control Chip read
= .07 (nc)

PROCEDURE NO: PRDP-30-01	ISSUE NO: 03	ATTACHMENT 4 PAGE NO: 1 OF 1

Figure 6-4. Example calibration form for the Harshaw 4000 dosimetry system.

can be calculated indirectly from routine dosimetry results. Due to the complexity of this calculation, however, SNL does not routinely calculate dose to the lens of the eye but instead uses an annual cumulative shallow dose equivalent of 1.5 rem as a benchmark value that triggers respective manual calculation and reporting of results (Walker 1997b). No information has been found on extremity calculation and reporting.

There are specific circumstances and respective protocols for making adjustments to an individual's recorded dose or estimating doses when reliable measurements are not available (Potter et al. 1993; SNL 1993c). Calculation or database programming errors are also included but do not necessarily involve an adjustment. For example, in 1997 a SANDOS programming oversight was discovered that had resulted in incorrect background subtractions since 1992 and therefore in slightly overestimated doses (Walker 1997c). The programming correction was made when discovered, but no adjustments to the affected records were implemented because the slight overestimations were considered conservative.

The angular dependence of the Harshaw 8812 TLD was studied by SNL as part of the DOELAP accreditation process (Friedman, Loudermilk, and Thompson 1991). A batch of 8812 TLDs was sent to the Pacific Northwest Laboratory, which maintains a National Institute of Standards and Technology-traceable irradiation and measurement quality assurance program, to assess the angular dependence of dosimeter readings for various exposure geometries. The results (Figure 6-5) led to a conclusion that the horizontal and vertical angular dependence of the TLD system SNL uses are acceptable and "comparable to or better than results for modern dosimetry systems."

Horizontal Orientation — Harshaw 8800/8812 TLD System

Category/Source	Test Depth	-85°	-60°	-30°	0°	+30°	+60°	+85°
IIIA (M150)	Deep	0.932	1.124	1.208	1.234	1.197	1.072	0.653
	Shallow	0.729	1.102	1.214	1.257	1.224	1.130	0.787
IIIA (M30)	Deep	0.881	0.907	1.133	1.197	1.046	0.801	0.200
	Shallow	0.268	0.741	1.170	1.211	1.158	0.760	0.162
IV	Deep	0.987	0.985	1.005	1.019	0.998	0.954	0.578
	Shallow	0.809	0.916	0.962	0.980	0.975	0.944	0.929
VA (^{90}Sr/^{90}Y)	Shallow	0.015	0.316	1.037	1.112	0.982	0.156	0.109
VI (moderated)	Deep	0.477	0.889	1.185	1.209	1.091	0.821	0.401
VI (unmoderated)	Deep	0.052	0.609	1.095	1.097	1.051	0.556	0.274

Vertical Orientation — Harshaw 8800/8812 TLD System

Category/Source	Test Depth	-85°	-60°	-30°	0°	+30°	+60°	+85°
IIIA (M150)	Deep	0.924	1.126	1.221	1.253	1.196	1.072	0.663
	Shallow	0.495	1.049	1.209	1.262	1.229	1.154	0.839
IIIA (M30)	Deep	0.589	0.899	1.150	1.183	1.098	0.804	0.291
	Shallow	0.142	0.705	1.141	1.146	1.113	0.810	0.178
IV	Deep	1.007	1.008	1.011	1.004	0.999	0.946	0.824
	Shallow	0.787	0.870	0.947	0.971	0.987	0.945	0.959
VA (^{90}Sr/^{90}Y)	Shallow	0.026	0.171	0.976	1.086	1.063	0.336	0.030
VI (moderated)	Deep	0.158	0.799	1.119	1.205	1.191	0.839	0.400
VI (unmoderated)	Deep	0.167	0.058	1.047	1.074	1.073	0.572	0.394

Figure 6-5. Angular dependence testing results for the Harshaw 8800/8812 dosimetry system. Results in each category are normalized (apparently to the average result from control cards exposed under the normal, perpendicular geometry).

The lower limits of detection (LLDs) for the Harshaw Model 8802 dosimeter were evaluated by SNL in 1997. Both monthly and quarterly exchange periods were tested within various DOELAP exposure categories, and the results are shown in Table 6-2. A 1990 LLD study for the Model 8801 dosimeter showed shallow dose equivalent LLD of about 31 mrem. The only difference between the Model 8802 and 8801 dosimeters is that the 8802 has a slightly thicker shallow chip. Because the shallow dose LLD for the newer 8802 cards is 10 mrem or less across all exposure categories, SNL uses a 10-mrem LLD value in SANDOS for shallow dose equivalent.

Table 6-2. Monthly and quarterly LLDs for the Harshaw Model 8802 dosimeter card (adapted from Walker, Loudermilk, and Thompson 1997).

Exposure category	Radiation types	Test depth	Monthly LLD (rem)	Quarterly LLD (rem)
I	Accident X-rays	Deep	0.003	0.004
II	Accident gammas	Deep	0.003	0.005
IIIA	General X-rays	Shallow	0.004	0.008
IIIA	General X-rays	Deep	0.004	0.006
IV	Cs-137 gammas	Shallow	0.003	0.007
IV	Cs-137 gammas	Deep	0.003	0.004
VA	Beta particles	Shallow	0.003	0.007
VI	Moderated neutrons	Deep	0.003	0.005

Exposure category VII (mixtures)

Component exposure categories	Test depth	Monthly LLD (rem)	Quarterly LLD (rem)
III + IV	Shallow	0.005	0.010
III + IV	Deep	0.004	0.006
III + VA	Shallow	0.004	0.008
III + VA	Deep	0.005	0.008
III + VI	Deep	0.003	0.004
IV + VA	Shallow	0.004	0.008
IV + VA	Deep	0.004	0.006
IV + VI	Deep	0.003	0.004

6.4.3 Exposure Energy Spectra

Dose reconstruction under the NIOSH program requires estimates of exposure percentages within specific energy bands for each type of radiation as follows (NIOSH 2007b):

- Photons:
  - <30 keV,
  - 30 to 250 keV, and
  - >250 keV.
- Beta particles:
  - >15 keV.
- Neutrons:
  - <10 keV,
  - 10 to 100 keV,
  - 100 keV to 2 MeV,
  - 2 to 20 MeV, and
  - >20 MeV.

For external exposures, betas with energies of less than 15 keV are not applicable. Table 6-3 provides estimates of percentages of radiation energies within each relevant category broken down by process within each facility. Most of these estimates were obtained from SNL-CA site personnel.

Other sources and assumptions are provided as applicable in the table footnotes. The TRL is not listed because the primary radionuclide was tritium with beta energies of less than 15 keV.

Table 6-3. Selection of radiation energies and percentages.

Weapons Laboratory Facility Complex (Buildings 910, 912, 913, 914, 916, 918), 1958 to 1998

Process description	Radiation type, energy selection (keV), and percentage[a]		
Test/repair of neutron and X-ray detectors (neutron and X-ray generators)	Photon	30–250	100
	Neutron	10–100	5
		100–2,000	5
		2,000–20,000	90
Wet machining of DU	Beta	>15	100
	Photon	30–250	90[b]
		>250	10[b]
Radiography for weapons components	Beta	>15	100
	Photon	30–250	50[b,c]
		>250	50[b,c]
Radiography for materials science studies (X–ray diffraction operations later moved to Building 941)	Beta	>15	100
	Photon	<30	40
		30–250	30
		>250	30
H-3 storage studies	Photon	30–250	50[b,d]
		>250	50[b,d]
Ion beam analysis of materials	Photon	30–250	30
		>250	70
Radiflo leak tests	Beta	>15	100
	Photon	30–250	10
		>250	90

Radiography (Building 923), unknown to early 1990s

Process description	Radiation type, energy selection (keV), and percentage[a]		
Radiography using X–rays, gamma rays, neutrons, alpha and beta particles	Beta	>15	100
	Photon	<30	5
		30–250	45
		>250	50
	Neutron	<10–100	5
		100–2,000	70
		>2,000–20,000	25

Micro and Nano Technologies Laboratories (Buildings 941, 942, 943), unknown to present

Process description	Radiation type, energy selection (keV), and percentage[a]		
Radiography using X–rays, gamma rays, neutrons, alpha and beta particles	Beta	>15	100
	Photon	<30	40
		30–250	30
		>250	30

Explosives and Environmental Testing Complex (Buildings 955, 956, 966, 972, 974, 976, 977, 978, 979, 981, 983), 1958 to present

Process description	Radiation type, energy selection (keV), and percentage[a]		
Environmental testing of mock up weapons and components (DU)	Beta	>15	100
	Photon	30–250	90[b]
		>250	10[b]

Storage Facilities (Buildings 921, 927, 961, 982), unknown to present

Process description	Radiation type, energy selection (keV), and percentage[a]		
Storage and packaging of waste materials	Beta	>15	100
	Photon	30–250	70
		>250	30

a. Estimated primarily by site personnel.
b. Based on default assumptions favorable to claimants for DU in ORAUT (2011).
c. Assumes radiography primarily associated with weapons mock-ups and DU.
d. Assumes only external exposures would be associated with DU beds in tritium storage facility.

6.4.3.1 Neutron Dose Conversion Factors

As described in ORAUT-OTIB-0055, *Technical Basis for Conversion from NCRP Report 38 Neutron Quality Factors to ICRP Publication 60 Radiation Weighting Factors for Respective IREP Input Neutron Energy Ranges* (ORAUT 2006b), adjustments to neutron dose are necessary to account for changes in quality factors between historical and current scientific guidance. Using the method in ORAUT-OTIB-0055, adjustment factors were determined for the various energy groups at the two SNL-CA facilities where neutron exposures were possible. Table 6-4 shows multiplier values to use for dose reconstruction.

Table 6-4. Neutron DCFs for applicable SNL-CA facilities.

Facility	Neutron energy intervals	NCRP 38 (NCRP 1971) quality factor	ICRP 60 (ICRP 1991) weighting factor	Dose fraction[a]	Corrected dose equivalent multiplier[b]
Weapons laboratory complex	10–100 keV	5.38	10	0.05	0.093
Weapons laboratory complex	0.1–2.0 MeV	10.49	20	0.05	0.095
Weapons laboratory complex	2.0–20.0 MeV	7.56	10	0.90	1.190
Radiography	10–100 keV	5.38	10	0.05	0.093
Radiography	0.1–2.0 MeV	10.49	20	0.70	1.335
Radiography	2.0–20.0 MeV	7.56	10	0.25	0.331

a. From Table 6-3.
b. Multiply reported dose by these factors to determine the corrected neutron dose equivalent for each applicable neutron energy interval.

6.4.4 Missed Dose

Given the lack of documentation about MDLs for dosimeter systems for the period from 1956 to 1988, it is necessary to estimate dosimeter system MDLs and missed dose. During this early period, it is reasonable to assume that MDLs for the various systems were similar to contemporary technologies in use at other AEC or DOE facilities during corresponding periods. Maximum annual missed doses were estimated using exchange periods and MDL/2 as recommended by NIOSH (NIOSH 2007b). For 1989 to the present, the MDL information in the previous section was used to estimate missed dose using exchange periods and MDL/2. Table 6-5 lists documented or estimated MDLs and maximum missed doses for each dosimetry technology SNL-CA used.

Table 6-5. Estimated maximum annual missed photon, beta, and neutron dose.

Period of use	Dosimeter	MDL (mrem)	Exchange frequency	Maximum annual missed dose (mrem)[a]
1956–1959	Two-element beta/photon film	30[b]	Monthly	180
1959–1971	Two-element beta/photon film	30[b]	Monthly	180
1956–1971	Neutrons (NTA film)	50[b]	Monthly	300
1972–1982	Two-chip TLD	20[c]	Semiannual	20
1982–1988	Three-chip Eberline TLD	20[c]	Annual; semiannual	10; 20
1972–1988	Neutrons (two- and three-chip TLD systems)[d]	20[c]	Annual; semiannual	10; 20
1989–1990	Multielement Harshaw TLD	10	Quarterly	20
1991–present	Multielement Harshaw TLD	10	Quarterly	20
1989–present	Neutrons (Harshaw TLD systems)	5	Quarterly	10

a. Maximum annual missed dose calculated using $N \times MDL/2$ from NIOSH (2007b).
b. Estimated MDL based on contemporary film systems of similar sensitivity (ORAUT 2007a).
c. Estimated MDL based on contemporary TLD systems of the period (ORAUT 2016, 2010b, 2006b).
d. Although neutron doses are reported for the two-chip system, no documentation of the neutron dosimetry methodology employed has been found.

6.4.5 Organ Dose Conversion Factors

During the period in which film dosimeters were used at SNL-CA, dosimeters were calibrated in units of roentgen. Limited information is available about calibration of TLDs for the period between 1972 and 1988, but it is favorable to claimants to assume TLDs were calibrated in units of exposure (roentgen). After dosimetry services were transferred to SNL-NM to gain DOELAP accreditation and consolidate all SNL dosimetry programs, the personal dose equivalent *Hp(10)* should be used. Table 6-6 shows dose units to use for organ DCFs.

Table 6-6. Dose units for organ DCFs.

Years	Photon dose units for use with organ DCFs
1956–1959	*R*
1959–1971	*R*
1972–1982	*R*
1982–1988	*R*
1989–1990	*Hp(10)*
1991–current	*Hp(10)*

6.4.6 Adjustments to Recorded Neutron Dose

Based on multiplying the data from the following three sections, the total correction factor for NTA neutron doses is 2.65.

6.4.6.1 Correction for Low-Energy Neutrons with NTA Neutron Dosimeters

Because NTA film is a poor detector of neutron energies below 500 to 800 keV (ORAUT 2014), a correction factor of 1.5 is applied, based on information from ORAUT-TKBS-0036-6, *Argonne National Laboratory-East – External Dosimetry* (ORAUT 2014).

6.4.6.2 Angular Dependence of NTA Neutron Dosimeters

The results of a study by Kathren, Prevo, and Block (1965) that indicated a correction of 1.3 is appropriate for NTA film for neutrons of energy greater than about 2 MeV. The data provided in the Kathren, Prevo, and Block study also indicated the dosimeters did not need correction at lower neutron energies.

6.4.6.3 Track Fading of Neutron NTA Dosimeters

RDC participated in testing of their film dosimeters, and the results for neutron exposures averaged 40% higher than the reported administered neutron exposures (RDC 1961, pp. 15–18). The exposures and results were reported in terms of neutron flux. A report describing their film dosimeters included the following (RDC 1958–1961, p. 23):

> *The NTA emulsion is subject to latent image track fading. The longer the period between exposure and development, the more pronounced is the fading. Fading is greatest for short tracks and is accelerated by high humidity. Where humidities are moderate, bi-weekly or monthly periods do not produce serious latent image fading unless low neutron energies are encountered. It is recommended that films be returned for processing immediately after the exposure period, preferably via air mail. Films are developed on the day they are received and reports are issued within 48 hours.*

The Mound Site determined that track fading was determined to be 9% per week. The NTA film was exchanged on a monthly cycle and therefore the correction for this effect is assumed to be 1.36 (Meyer 1994, Volume IV, pp, 171–177, 181–185).

6.4.7 Uncertainty

Given the lack of specific technical information available about dosimetry systems for much of the SNL-CA site history, it is necessary to estimate measurement uncertainty based on reported values for contemporary systems in use at other facilities. Table 6-7 shows estimates based on ORAUT-TKBS-0012-6, *Oak Ridge National Laboratory – Occupational External Dose* (ORAUT 2007a). Some general analogies can be drawn between ORNL and SNL-CA in terms of dosimetry technologies in use during various periods of interest.

Table 6-7. Systematic uncertainty estimates (adapted from ORAUT 2007a).

Dosimeter	Period of use	Systematic[a] uncertainty factors
Two-element film	1956–1971	1.3
Two-chip TLD	1972–1982	1.15
Three-chip TLD	1982–1988	1.15
Multielement TLD	1989–present	1.15

a. Systematic uncertainty from lack of knowledge about energy distributions and geometries.

For neutrons, the biases are corrected as described in Section 6.4.6. The uncertainty factor is 1.3 [5].

7.0 ATTRIBUTIONS AND ANNOTATIONS

Where appropriate in this document, 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 in the Attributions and Annotations section, with information to identify the source and justification for each associated item. Conventional References, which are provided in the next section of this document, link data, quotations, and other information to documents available for review on the Project's Site Research Database (SRDB).

[1] Thomas, Elyse. ORAU Team. Principal Medical Dosimetry Scientist. October 2006.
The X-ray record form included in claim files has a place for the technician to record the projection, mA, kVp, distance, and time. For PA chests, the mA is almost always listed as 5, the distance is listed as 72", and the kVp is usually around 70. Exposure times are not usually listed. It is assumed that the person completing this part of the X-ray record form was recording the mAs, not the mA, primarily because radiographic machines are not designed to operate at such low mA settings and also because time settings were not recorded. Five mAs would not be unusual for a PA chest exposure.

[2] Lopez, Theresa. ORAU Team. Senior Toxicologist. September 2006.
Lumbar spine X-rays were performed at hire from 1956 through 1971 as evidenced by medical records in claim files.

[3] Lopez Theresa. ORAU Team. Senior Toxicologist. September 2006.
According to a review of X-ray records and at the direction of ORAU in comments dated October 2006, the X-ray machines have been assumed to be single-phase.

[4] Lopez Theresa. ORAU Team. Senior Toxicologist. September 2006.
Lumbar spine X-rays were performed at hire from 1956 through 1971 as evidenced by medical records in claim files.

[5] Rohrig, Norman D. ORAU Team. Health Physicist. April 2006.
This standard ORAU Team TBD table is based on information in Attachment A and an understanding of error propagation.

REFERENCES

Adolphson, D. R., 1972, "Machining Test Specimens in Uranium Alloys," memorandum to J. F. Bryson, Sandia Laboratories, Livermore, California, April 7. [SRDB Ref ID: 23662]

AEC (U.S. Atomic Energy Commission), 1963, "Standards for Radiation Protection," Chapter 0524, *AEC Manual*, Washington, D.C., August 12. [SRDB Ref ID: 13037]

AEC (U.S. Atomic Energy Commission), 1960, *Annual Report of Health and Safety Division, 1959, Idaho Operations Office*, IDO-12014, Idaho Operations Office, Idaho Falls, Idaho, October. [SRDB Ref ID: 8080]

Althouse, P. E., N. A. Bertoldo, R. G. Blake, S. L. Brigdon, R. A. Brown, C. G. Campbell, E. Christofferson, L. M. Clark, K. J. Folks, G. M. Gallegos, A. R. Grayson, R. J. Harrach, J. M. Larson, D. H. MacQueen, S. Mathews, B. Nisbet, S. R. Peterson, M. J. Taffet, P. J. Tate, R. J. Vellinger, and R. A. Williams, 2001, *Environmental Report 2000*, *Data Supplement*, UCRL-50027-00, N. J. Woods and L. L. Powers, editors, University of California, Lawrence Livermore National Laboratory, Livermore, California, September 1. [SRDB Ref ID: 140703]

Author unknown, 1988, "Tritium Research Laboratory Health Physics Quarterly Summary, Hazards Control Division, October 1988," October. [SRDB Ref ID: 23135]

Author unknown, 1989a, "Tritium Research Laboratory Health Physics Quarterly Summary, Hazards Control Division #8514, January 1989," January. [SRDB Ref ID: 23137]

Author unknown, 1989b, "Tritium Research Laboratory Health Physics Quarterly Summary, Hazards Control Division, April 1989," April. [SRDB Ref ID: 23225]

Author unknown, 1989c, "Tritium Research Laboratory Health Physics Quarterly Report, Hazards Control Division, July 1989," July. [SRDB Ref ID: 23226]

Author unknown, 1989d, "Tritium Research Laboratory Health Physics Quarterly Report, Hazards Control Division, October 1989," October. [SRDB Ref ID: 23227]

Auyong, M., K. S. Griggs, and R. W. Buddemeier, 1982, *Environmental Monitoring at the Lawrence Livermore National Laboratory, 1981 Annual Report*, UCRL-50027-81, University of California, Lawrence Livermore National Laboratory, Livermore, California, March 11. [SRDB Ref ID: 23397]

Biermann, A. H., P. E. Althouse, N. A., Bertoldo, R. G. Blake, S. L. Brigdon, R. A. Brown, C. G. Campbell, E. Christofferson, L. M. Clark, K. J. Folks, G. M. Gallegos, A. R. Grayson, R. J. Harrach, J. M. Larson, D. H. MacQueen, S. Mathews, B. Nisbet, S. R. Peterson, M. J. Taffet, P. J. Tate, R. J. Vellinger, and R. A. Williams, 2001, *Environmental Report 2000*, UCRL-50027-00, N. J. Woods and L. L. Powers, editors, University of California, Lawrence Livermore National Laboratory, Livermore, California, September 1. [SRDB Ref ID: 23031]

Bradley, E. W., F. R. Loudermilk, D. C. Ward, and A. L. Stanley, 1993, *Source Normalization and Traceability of the HF-870 $^{90}Sr/^{90}Y$ Source for the Harshaw Model 8800 TLD Reader System*, Sandia National Laboratories, Albuquerque, New Mexico. [SRDB Ref ID: 23577, p. 5]

Bradley, E. W., F. R. Loudermilk, D. C. Ward, and A. L. Stanley, 1994, *Harshaw Dose Calculation Algorithm*, Issue 3, Sandia National Laboratories, Albuquerque, New Mexico. [SRDB Ref ID: 23577, p. 429]

Bradley, E. W., F. R. Loudermilk, J. A. Zamora, and S. W. Walker, 1995, *Harshaw 8800 TLD Card Reader – Daily Calibration*, (RPXD-13-06 Manual), Issue 7, Sandia National Laboratories, Albuquerque, New Mexico. [SRDB Ref ID: 19093]

Brekke, D. D., 1990, *Site Environmental Report for 1989*, SAND-90-8016, Sandia National Laboratories, Livermore, California, September. [SRDB Ref ID: 23543]

Brekke, D. D., 1991, *Site Environmental Report for 1990*, SAND-91-8006, Sandia National Laboratories, Livermore, California. [SRDB Ref ID: 22972]

Brekke, D. D., and R. C. Holland, 1992, *Site Environmental Report for 1991*, SAND-92-8001, Sandia National Laboratories, Livermore, California. [SRDB Ref ID: 22973]

Brekke, D. D., and R. C. Holland, 1993, *Site Environmental Report for 1992*, SAND-93-8015, Sandia National Laboratories, Livermore, California. [SRDB Ref ID: 23546]

Brekke, D. D., and R. C. Holland, 1994, *Site Environmental Report for 1993*, SAND-94-8006, Sandia National Laboratories, Livermore, California. [SRDB Ref ID: 23131]

Brekke, D. D., and R. C. Holland, 1995, *Site Environmental Report for 1994*, SAND-95-8006, Sandia National Laboratories, Livermore, California. [SRDB Ref ID: 23547]

Bryson, J. F., 1972, *Machining Test Specimens in Uranium Alloys*, memorandum to W. T. Ryan, Sandia National Laboratories, Livermore, California, April 12. [SRDB Ref ID: 23662, p. 2]

Burke, J. F., 1969, "Reporting of Radiation Exposure Information to a Central Repository," memorandum to AEC Offices, Sandia National Laboratories, Livermore, California, January 8. [SRDB Ref ID: 24827, p. 84]

Carter, W., 2009, "Document Review Request," e-mail from W. Carter to C. Kirkwood, ORAU Team, August 3. [SRDB Ref ID: 71381]

Cipperley, F. V., 1966, *A General Summary of Personnel Monitoring Systems Utilized at the National Reactor Testing Station*, IDO-12056, U.S. Atomic Energy Commission, Idaho Operations Office, Idaho Falls, Idaho, September. [SRDB Ref ID: 8130]

DeSelm, C. H., 1965, *Film Dosimetry Program*, 1965, memorandum to B. S. Biggs, National Laboratories, Livermore Laboratory, California, October 6. [SRDB Ref ID: 23684]

Devlin, T. K., 1986, *1985 Environmental Monitoring Report, Sandia National Laboratories, Livermore, California*, SAND86-8012, Sandia National Laboratories, Livermore, California, April. [SRDB Ref ID: 22977]

Devlin, T. K., 1987, *1986 Environmental Monitoring Report, Sandia National Laboratories, Livermore, California*, SAND87-8210, Sandia National Laboratories, Livermore, California, April. [SRDB Ref ID: 22978]

Devlin, T. K., 1988, *1987 Environmental Monitoring Report, Sandia National Laboratories, Livermore, California*, SAND88-8206, Sandia National Laboratories, Livermore, California, April. [SRDB Ref ID: 22979]

DOE (U.S. Department of Energy), 1981, "Personnel Dosimetry Performance," memorandum to file from Dosimetry Branch, Idaho Operations Office, Idaho Falls, Idaho, January 8. [SRDB Ref ID: 8125]

DOE (U.S. Department of Energy), 1982, Final Environmental Impact Statement for Lawrence Livermore National Laboratory and Sandia National Laboratories-Livermore Sites, DOE/EIS-0028, Livermore, California, July. [SRDB Ref ID: 22980]

DOE (U.S. Department of Energy), 1986a, Department of Energy Standard for the Performance Testing of Personnel Dosimetry Systems, DOE Laboratory Accreditation Program for Personnel Dosimetry Systems, DOE/EH-0027, Assistant Secretary for Environment, Safety, and Health, Washington, D.C., December. [SRDB Ref ID: 12294]

DOE (U.S. Department of Energy), 1988, *Radiation Protection for Occupational Workers*, Order 5480.11, Office of Environment, Safety and Health, Washington, D.C., December 21. [SRDB Ref ID: 8073]

DOE (U.S. Department of Energy), 1990, *Tiger Team Assessment of the Sandia National Laboratories, Livermore, California*, DOE/EH-0141, Washington, D.C., August. [SRDB Ref ID: 23554]

DOE (U. S. Department of Energy), 1992, Final Environmental Impact Statement and Environmental Impact Report for Continued Operation of Lawrence Livermore National Laboratory and Sandia National Laboratories, DOE/EIS-0157, Livermore, California, August. [SRDB Ref ID: 15935]

DOE (U.S. Department of Energy), 1993, 10 CFR 835, Occupational Radiation Protection, Final Rule, December 14, 1993, Federal Register, Vol. 58, No. 238, Washington, D.C. [SRDB Ref ID: 176022]

DOE (U. S. Department of Energy), 2003, *Final Site-Wide Environmental Assessment (SWEA) for Sandia National Laboratories/California*, DOE/EA-1422, National Nuclear Security Administration, Albuquerque, New Mexico, January. [SRDB Ref ID: 28165]

DOE (U.S. Department of Energy), 2006, DOE Facts: Declassification of Today's Highly Enriched Uranium Inventories at Department of Energy Laboratories, Office of the Press Secretary, Washington, D.C. [SRDB Ref ID: 33207]

Friedman, L. F., F. R. Loudermilk, and D. J. Thompson, 1991, *Angular Dependence of the Harshaw 8800/8812 TLD System*, Sandia National Laboratories, Albuquerque, New Mexico. [SRDB Ref ID: 23577, p. 221]

Gallegos, G. M., J. M. Sims, K. A. Surano, K. C. Lamson, and M. G. Brown, editors, 1990, *Environmental Report for 1989*, UCRL-50027-89, University of California, Lawrence Livermore National Laboratory, Livermore, California. [SRDB Ref ID: 26724]

Gallegos, G. M., B. K. Balke, K. A. Surano, W. G. Hoppes, P. J. Tate, J. C. Steenhoven, B. C. Fields, L. M. Garcia, K. C. Lamson, A. L. Lamarre, R. A. Failor, K. G. Fischer, F. S. Miller, D. W. Rueppel, R. W. Bainer, and J. M. Sims, 1992, *Environmental Report for 1991*, UCRL-50027-91, S. Hunter and G. Wilt, editors, University of California, Lawrence Livermore National Laboratory, Livermore, California. [SRDB Ref ID: 23036]

Gallegos, G. M., S. M. Wander, B. K. Balke, E. Christofferson, P. J. Tate, K. A. Surano, R. J. Harrach, L. M. Garcia, B. C. Fields, W. G. Hoppes, R. A. Failor, A. L. Lamarre, R. G. Blake, D. W. Rueppel, W. F. Isherwood, D. H. MacQueen, and R. L. Berger, 1993, *Environmental Report 1992*, UCRL-50027-92, G. C. Wilt, editor, University of California, Lawrence Livermore National Laboratory, Livermore, California. [SRDB Ref ID: 23037]

Gallegos, G. M., P. J. Tate, B. K. Balke, E. Christofferson, R. J. Harrach, W. G. Hoppes, R. A. Failor, S. M. Wander, B. C. Fields, L. M. Garcia, A. R. Grayson, K. A. Surano, D. H. MacQueen, R. G. Blake, M. J. Taffet, S. J. Coleman, C. H. Grandfield, C. M. Van Warmerdam, J. M. Larson, F. J. Gouveia, and W. F. Isherwood, 1994, *Environmental Report 1993*, UCRL-50027-93, G. C. Wilt, editor, University of California, Lawrence Livermore National Laboratory, Livermore, California, September 1. [SRDB Ref ID: 23038]

Gallegos, G. M., P. E. Althouse, N. A. Bertoldo, R. G. Blake, S. L. Brigdon, R. A. Brown, C. G. Campbell, E. Christofferson, L. M. Clark, A. R. Grayson, R. J. Harrach, H. E. Jones, D. H. MacQueen, S. Mathews, S. R. Peterson, M. A. Revelli, L. Sanchez, M. J. Taffet, P. J. Tate, R. Ward, and R. A. Williams, 2002, *Environmental Report 2001*, UCRL-50027-01, N. J. Woods and J. Kohl, editors, University of California, Lawrence Livermore National Laboratory, Livermore, California, September 1. [SRDB Ref ID: 23032]

Gallegos, G. M., P. E. Althouse, N. A. Bertoldo, R. G. Blake, S. L. Brigdon, R. A. Brown, C. G. Campbell, E. Christofferson, L. M. Clark, A. R. Grayson, R. J. Harrach, H. E. Jones, D. H. MacQueen, S. Mathews, S. R. Peterson, M. A. Revelli, L. Sanchez, M. J. Taffet, P. J. Tate, R. Ward, and R. A. Williams, 2002, *Environmental Report 2001*, *Data Supplement*, UCRL-50027-01, N. J. Woods and J. Kohl, editors, University of California, Lawrence Livermore National Laboratory, Livermore, California, September 1. [SRDB Ref ID: 140704]

Gallegos, G., N. A. Bertoldo, C. G. Campbell, S. Cerruti, V. Dibley, J. L. Doman, A. R. Grayson, H. E. Jones, G. Kumamoto, D. H. MacQueen, J. C. Nelson, L. Paterson, M. A. Revelli, A. M. Wegrecki, K. Wilson, and J. Woollett, 2009, *Environmental Report 2008*, UCRL-50027-08, N. J. Woods, editor, Lawrence Livermore National Security, Lawrence Livermore National Laboratory, Livermore, California, August 31. [SRDB Ref ID: 137257]

Gallegos, G., N. A. Bertoldo, R. Blake, C. G. Campbell, S. Cerruti, J. Cody, V. Dibley, J. L. Doman, A. R. Grayson, H. E. Jones, G. Kumamoto, D. H. MacQueen, J. C. Nelson, L. Paterson, M. A. Revelli, A. M. Wegrecki, K. Wilson, and J. Woollett, 2010, *Environmental Report 2009*, UCRL-TR-50027-09, N. J. Woods, editor, Lawrence Livermore National Security, Lawrence Livermore National Laboratory, Livermore, California, August 31. [SRDB Ref ID: 140705]

Garcia, T., 1990a, *Tritium Research Laboratory Health Physics Quarterly Report, Hazards Control Division, January 1990,* Sandia National Laboratories, Livermore, California, January. [SRDB Ref ID: 23228]

Garcia, T., 1990b, *Tritium Research Laboratory Health Physics Quarterly Report, Health and Safety Division, April 1990,* Sandia National Laboratories, Livermore, California, April. [SRDB Ref ID: 23232]

Garcia, T., 1990c, *Tritium Research Laboratory Health Physics Quarterly Summary, Health and Safety Division, July 1990*, Sandia National Laboratories, Livermore, California, July. [SRDB Ref ID: 23233]

Garcia, T., 1990d, *Tritium Research Laboratory Health Physics Quarterly Summary, Health and Safety Division, October 1990*, Sandia National Laboratories, Livermore, California, October. [SRDB Ref ID: 23239]

Garcia, T. B., 1991a, "Bioassay Program Requirements," memorandum to K. K. Babcock, Sandia National Laboratories, Livermore, California, April 3. [SRDB Ref ID: 23664, p. 3]

Garcia, T. B., 1991b, "Radioactive/Mixed Waste Operations @ Bldgs. 961 & 968," memorandum to D. A. Wright, Sandia National Laboratories, Livermore, California, May 24. [SRDB Ref ID: 23664, p. 4]

Garcia, T., 1991c, *Tritium Research Laboratory Health Physics Quarterly Report, Health and Safety Division, April 1991*, Sandia National Laboratories, Livermore, California, April. [SRDB Ref ID: 23243]

Garcia, T., 1991d, *Tritium Research Laboratory Health Physics Quarterly Report, Health and Safety Division, JAN 1991*, Sandia National Laboratories, Livermore, California, January. [SRDB Ref ID: 23240]

Garcia, T., 1991e, *Tritium Research Laboratory Health Physics Quarterly Report, Health and Safety Division, July 1991*, Sandia National Laboratories, Livermore, California, July. [SRDB Ref ID: 23244]

Garcia, T., 1991f, *Tritium Research Laboratory Health Physics Quarterly Report, Health and Safety Division, October 1991*, Sandia National Laboratories, Livermore, California, October. [SRDB Ref ID: 23246]

Garcia, T., 1992a, *Tritium Research Laboratory Health Physics Quarterly Summary, Health and Safety Division, January 1992*, Sandia National Laboratories, Livermore, California, January. [SRDB Ref ID: 23247]

Garcia, T., 1992b, *Tritium Research Laboratory Health Physics Quarterly Summary, Health and Safety Division, April 1992*, Sandia National Laboratories, Livermore, California, April. [SRDB Ref ID: 23252]

Garcia, T., 1992c, *Tritium Research Laboratory Health Physics Quarterly Summary, Health and Safety Division, July 1992*, Sandia National Laboratories, Livermore, California, July. [SRDB Ref ID: 23259]

Garcia, T., 1992d, *Tritium Research Laboratory Health Physics Quarterly Summary, Health and Safety Division, October 1992*, Sandia National Laboratories, Livermore, California, October. [SRDB Ref ID: 23262]

Garcia, T., 1993a, *Tritium Research Laboratory Health Physics Quarterly Summary, Health and Safety Division, January 1993*, Sandia National Laboratories, Livermore, California, January. [SRDB Ref ID: 23263]

Garcia, T., 1993b, *Tritium Research Laboratory Health Physics Quarterly Summary, Health and Safety Division, April 1993*, Sandia National Laboratories, Livermore, California, April. [SRDB Ref ID: 23264]

Garcia, T., 1993c, *Tritium Research Laboratory Health Physics Quarterly Summary, Health and Safety Division, July 1993*, Sandia National Laboratories, Livermore, California, July. [SRDB Ref ID: 23265]

Garcia, T., 1993d, *Tritium Research Laboratory Health Physics Quarterly Summary, Health and Safety Division, October 1993*, Sandia National Laboratories, Livermore, California, October. [SRDB Ref ID: 23267]

Garcia, T., 1994a, *Tritium Research Laboratory Health Physics Quarterly Summary, Health Protection Department, January 1994*, Sandia National Laboratories, Livermore, California, January. [SRDB Ref ID: 23334]

Garcia, T., 1994b, *Tritium Research Laboratory Health Physics Quarterly Summary, Health Protection Department, April 1994*, Sandia National Laboratories, Livermore, California, April. [SRDB Ref ID: 23336]

Garcia, T., 1994c, *Tritium Research Laboratory Health Physics Quarterly Summary, Health Protection Department, July 1994*, Sandia National Laboratories, Livermore, California, July. [SRDB Ref ID: 23346]

Garcia, T., 1994d, *Tritium Research Laboratory Health Physics Quarterly Summary, Health Protection Department, October 1994*, Sandia National Laboratories, Livermore, California, October. [SRDB Ref ID: 23347]

Garcia, T., 1995, *TRL Health Physics Quarterly Report*, *Health Protection Department, First Quarter*, Sandia National Laboratories, Livermore, California. [SRDB Ref ID: 23348]

Garcia, T. B., and T. P. Gorman, 1996, *Radiological Characterization and Final Facility Status Report Tritium Research Laboratory*, SAND96-8004, Sandia National Laboratories, Livermore, California, August. [SRDB Ref ID: 22982]

Gesell, T. F., 1982, "Calibration of the INEL Personnel Dosimeter for Non-Penetrating Radiation," letter to S. Marchetti (West Valley Nuclear Services), U.S. Department of Energy, Idaho Operations Office, Idaho Falls, Idaho, October 26. [SRDB Ref ID: 8127]

Griggs, K. S., M. A. Gonzalez, and R. W. Buddemeier, 1983, *Environmental Monitoring at the Lawrence Livermore National Laboratory, 1982 Annual Report*, UCRL-50027-82, University of California, Lawrence Livermore National Laboratory, Livermore, California, March 14. [SRDB Ref ID: 30124]

Griggs, K. S., D. S. Myers, and R. W. Buddemeier, 1984, *Environmental Monitoring at the Lawrence Livermore National Laboratory, 1983 Annual Report*, UCRL-50027-83, University of California, Lawrence Livermore National Laboratory, Livermore, California, February. [SRDB Ref ID: 23419]

Griggs, K. S., D.S. Meyers, and R. W. Buddemeier, 1985, *Environmental Monitoring at the Lawrence Livermore National Laboratory, 1984 Annual Report*, UCRL-50027-84, University of California, Lawrence Livermore National Laboratory, Livermore, California, February. [SRDB Ref ID: 55783]

Griggs, K. S., and R. W. Buddemeier, 1986, *Environmental Monitoring at the Lawrence Livermore National Laboratory, 1985 Annual Report*, UCRL-50027-85, University of California, Lawrence Livermore National Laboratory, Livermore, California, February. [SRDB Ref ID: 14836]

Gudiksen, P. H., C. L. Lindeken, C. Gatrousis, and L. R. Anspaugh, 1972, *Environmental Levels of Radioactivity in the Vicinity of the Lawrence Livermore Laboratory, January through December 1971*, UCRL-51242, University of California, Lawrence Livermore Laboratory, Livermore, California, June 14. [SRDB Ref ID: 23907]

Gudiksen, P. H., C. L. Lindeken, J. W. Meadows, and K. O. Hamby, 1973, *Environmental Levels of Radioactivity in the Vicinity of the Lawrence Livermore Laboratory, 1972 Annual Report*, UCRL-51333, University of California, Lawrence Livermore Laboratory, Livermore, California, March 7. [SRDB Ref ID: 23909]

Gupta, V. P., 1981, *Standardization and Use of 2.5 Ci 90Sr/90Y Source for Calibration of Personnel Dosimeters and Portable Instruments*, IDO-12093, U.S. Department of Energy, Idaho Operations Office, Idaho Falls, Idaho. [SRDB Ref ID: 8155]

Hafner, R. S, 1980, *TRL Health Physics Summary, First Quarter, 1980*, memorandum, Sandia Laboratories, Albuquerque, New Mexico, and Livermore, California, April 11. [SRDB Ref ID: 23669, p. 81]

Hafner, R. S., 2006, *Notes from Telephone Conversations on 4/26/06 and 5/5/06*, interviewed by L. McDowell-Boyer, Livermore, California, September 14. [SRDB Ref ID: 26842]

Hallman, A. K., 1989, *Radiation Dosimetry Data – File Format*, memorandum to E. Joiner, Sandia National Laboratories, Livermore, California, October 13. [SRDB Ref ID: 24810]

Hallman, A. K., 1990, *Dosimetry Data for SNLL*, memorandum to D. Thompson at SNL-NM, Sandia National Laboratories, Livermore, California, February 20. [SRDB Ref ID: 19271]

Harrach, R. J., G. M. Gallegos, R. A. Failor, E. Christofferson, P. J. Tate, E. R. Brandstetter, J. M. Larson, J. R. McIntyre, B. C. Fields, R. A. Brown, L. M. Garcia, A. R. Grayson, K. A. Surano, S. J. Coleman, B. J. Qualheim, M. J. Taffet, D. H. MacQueen, R. G. Blake, F. J. Gouveia, J. M. Bennett, M. Mlekush, S. P. Mancieri, J. S. Woollett, Jr., S. P. Harris, K. J. Folks, A. H. Biermann, R. J. Vellinger, K. C. Zahn, T. M. Carlsen, C. Van Warmerdam, B. K. Balke, S. Mathews, W. G. Hoppes, and C. H. Grandfield, 1995, *Environmental Report 1994*, UCRL-50027-94, K. S. Rath, editor, University of California, Lawrence Livermore National Laboratory, Livermore, California, September 1. [SRDB Ref ID: 16193]

Harrach, R. J., R. A. Failor, G. M. Gallegos, P. J. Tate, E. Christofferson, E. R. Brandstetter, J. M. Larson, A. H. Biermann, R. A. Brown, B. C. Fields, L. M. Garcia, A, R. Grayson, M. J. Taffet, R. G. Blake, K. A. Surano, J. H. White, S. J. Coleman, C. E. DeGrange, J. Celeste, D. H. MacQueen, E. Eagan, K. J. Folks, F. J. Gouveia, S. P. Harris, D. M. Chase, J. M. Bennett, M. Mlekush, S. P. Mancieri, J. S. Woollett, Jr., K. C. Zahn, R. J. Vellinger, T. M. Carlsen, C. van Warmerdam, J. R. McIntyre, S. Mathews, S. S. Goodwin, D. Rice, W. G. Hoppes, B. J. Qualheim, C. H. Grandfield, R. Ragaini, and J. Sims, 1996, *Environmental Report 1995*, UCRL-50027-95, H. L. Lentzner, editor, University of California, Lawrence Livermore National Laboratory, Livermore, California, September 3. [SRDB Ref ID: 23040, 23041]

Harrach, R. J., G. M. Gallegos, P. J. Tate, E. Christofferson, E. R. Brandstetter, J. M. Larson, A. H. Biermann, B. C. Fields, L. M. Garcia, K. A. Surano, R. J. Vellinger, S. J. Coleman, K. J. Folks, R. A. Brown, J. Celeste, D. H. MacQueen, F. J. Gouveia, M. J. Taffet, R. G. Blake, P. Althouse, W. Burks-Houck, S. Mathews, S. L. Brigdon, A. R. Grayson, C. E. DeGrange, J. M. Woods, W. E. Montemayor, H. K. Otsuki, C. Van Warmerdam, E. Eagan-McNeill, S. P. Harris, J. M. Bennett, M. L. Mlekush, S. P. Mancieri, J. S. Woollett, Jr., K. C. Zahn, T. M. Carlsen, J. R. Mc Intyre, D. W. Rice, Jr., W. G. Hoppes, C. H. Grandfield, C. S. Jackson, G. A. May, J.

Sims, and R. Ragaini, 1997, *Environmental Report 1996*, UCRL-50027-96, H. L. Lentzner and M. M. Napolitano, editors, University of California, Lawrence Livermore National Laboratory, Livermore, California. [SRDB Ref ID: 23042, 23043]

Harrach, R. J., J. M. Larson, G. M. Gallegos, E. Christofferson, E. R. Brandstetter, P. J. Tate, A. H. Biermann, B. C. Fields, L. M. Garcia, P. Althouse, R. J. Vellinger, S. J. Coleman, K. J. Folks, R. A. Brown, J. Celeste, K. A. Surano, M. J. Taffet, R. G. Blake, D. H. MacQueen, F. J. Gouveia, W. Burks-Houck, S. Mathews, J. R. Merrigan, S. L. Brigdon, A. R. Grayson, J. M. Woods, D. H. Armstrong, H. K. Otsuki, C. Van Warmerdam, S. P. Harris, J. M. Bennett, R. K. Henry, D. W. Short, J. C. Steenhoven, S. P. Mancieri, J. S. Woollett, Jr., K. C. Zahn, T. M. Carlsen, C. E. DeGrange, J. R. Mc Intyre, W. G. Hoppes, C. H. Grandfield, C. S. Jackson, K. V. Gilbert, and R. K. Hollister, 1998, *Environmental Report 1997*, UCRL-50027-97, H. L. Lentzner and J. C. Morris, editors, University of California, Lawrence Livermore National Laboratory, Livermore, California, September 1. [SRDB Ref ID: 23044]

Holland, R. C., 1997, *Site Environmental Report for 1996*, SAND-97-8015, Sandia National Laboratories, Livermore, California, August. [SRDB Ref ID: 22986]

Holland, R. C., 1998, *Site Environmental Report for 1997*, SAND98-8001, Sandia National Laboratories, Livermore, California, June. [SRDB Ref ID: 22987]

Holland, R. C., 1999, *Site Environmental Report for 1998*, SAND99-8004, Sandia National Laboratories, Livermore, California, June. [SRDB Ref ID: 22921]

Holland, R. C., 2000, *Site Environmental Report for 1999*, SAND2000-8254, Sandia National Laboratories, Livermore, California, September. [SRDB Ref ID: 22922]

Holland, R. C., 2001, *Site Environmental Report for 2000*, SAND2001-8525, Sandia National Laboratories, Livermore, California. [SRDB Ref ID: 32659]

Holland, R. C., 2002, *Site Environmental Report for 2001*, SAND2002-8337, Sandia National Laboratories, Livermore, California, July. [SRDB Ref ID: 22923]

Holland, R. C., and D. D. Brekke, 1988, *Environmental Monitoring at the Lawrence Livermore National Laboratory, Annual Report 1987*, UCRL-50027-87, University of California, Lawrence Livermore National Laboratory, Livermore, California, April. [SRDB Ref ID: 14838]

Holland, R. C., and D. D. Brekke, 1996, *Site Environmental Report for 1995*, SAND-96-8007, Sandia National Laboratories, Livermore, California, July. [SRDB Ref ID: 22983]

Holland, R. C., R. W. Buddemeier, and D. D. Brekke, 1987, *Environmental Monitoring at the Lawrence Livermore National Laboratory, 1986 Annual Report*, UCRL-50027-86, University of California, Lawrence Livermore National Laboratory, Livermore, California, April. [SRDB Ref ID: 23034]

Horan, J. R., 1962, *Health and Safety Division Annual Report 1961*, IDO-12021, U.S. Atomic Energy Commission, Idaho Operations Office, Idaho Falls, Idaho, May 21. [SRDB Ref ID: 8076]

ICRP (International Commission on Radiological Protection), 1982, *Protection of the Patient in Diagnostic Radiology*, Publication 34, Pergamon Press, Oxford, England. [SRDB Ref ID: 32466]

ICRP (International Commission on Radiological Protection), 1991, *1990 Recommendations of the International Commission on Radiological Protection*, Publication 60, Pergamon Press, Oxford, England. [SRDB Ref ID: 11517]

ICRP (International Commission on Radiological Protection), 1994, *Human Respiratory Tract Model for Radiological Protection*, Publication 66, Pergamon Press, Oxford, England. [SRDB Ref ID: 22732]

JCGM (Joint Committee for Guides in Metrology), 2008, *International Vocabulary of Metrology – Basic and General Concepts and Associated Terms (VIM)*, 3rd Edition. [SRDB Ref ID: 183484]

Jones, H. E., D. Armstrong, R. Blake, N. A. Bertoldo, C. G. Campbell, S. Cerruti, J. Cody, V. Dibley, J. L. Doman, G. Gallegos, A. R. Grayson, K. Heidecker, R. Hollister, G Kumamoto, D. H. MacQueen, J. C. Nelson, L. Paterson, M. A. Revelli, C. Rosene, A. Terrill, A. M. Wegrecki, K. Wilson, and J. Woollett, 2011, *Environmental Report 2010*, UCRL-TR-50027-10, K. Fury, editor, Lawrence Livermore National Security, Lawrence Livermore National Laboratory, Livermore, California, September 12. [SRDB Ref ID: 137256]

Jones, H. E., D. Armstrong, R. Blake, N. A. Bertoldo, S. Cerruti, V. Dibley, J. L. Doman, A. R. Grayson, K. Heidecker, R. Hollister, G Kumamoto, D. H. MacQueen, J. C. Nelson, H. Ottaway, L. Paterson, M. A. Revelli, C. Rosene, A. Terrill, A. M. Wegrecki, K. Wilson, and J. Woollett, 2012, *Environmental Report 11*, UCRL-TR-50027-11, H. Jones, editor, Lawrence Livermore National Security, Lawrence Livermore National Laboratory, Livermore, California, August 29. [SRDB Ref ID: 140878]

Jones, H. E., D. Armstrong, R. Blake, N. A. Bertoldo, S. Cerruti, C. Fish, V. Dibley, J. L. Doman, A. R. Grayson, K. Heidecker, R. Hollister, G. Kumamoto, D. H. MacQueen, J. C. Nelson, H. Ottaway, L. Paterson, M. A. Revelli, C. Rosene, A. Terrill, A. M. Wegrecki, K. Wilson, and J. Woollett, 2013, *Environmental Report 2012*, UCRL-TR-50027-12, H. Jones, editor, Lawrence Livermore National Security, Lawrence Livermore National Laboratory, Livermore, California, October 1. [SRDB Ref ID: 140879]

Jones, H. E., N. A. Bertoldo, R. Blake, J. Byrne, S. Cerruti, V. Dibley, J. L. Doman, C. Fish, A. R. Grayson, K. Heidecker, G. Kumamoto, D. H. MacQueen, W. Montemayor, H. Ottaway, L. Paterson, M. A. Revelli, C. Rosene, A. Terrill, A. M. Wegrecki, K. Wilson, J. Woollett, and R. Veseliza, 2014, *Environmental Report 2013*, UCRL-TR-50027-13, H. Jones, editor, Lawrence Livermore National Security, Lawrence Livermore National Laboratory, Livermore, California, October 1. [SRDB Ref ID: 140647]

Jones, H. E., N. Bertoldo, R. Blake, M. Buscheck, J. Byrne, S. Cerruti, C. Fish, M. Fratanduono, A. Grayson, D. MacQueen, W. Montemayor, H. Ottaway, L. Paterson, M. Revelli, C. Rosene, K. Swanson, A. Terrill, A. Wegrecki, K. Wilson, and J. Woollett, 2015, *Environmental Report 2014*, UCRL-TR-50027-14, H. Jones, editor, Lawrence Livermore National Security, Lawrence Livermore National Laboratory, Livermore, California, October 1. [SRDB Ref ID: 175546]

Kamelgarn, M. B., editor, 1989, *Environmental Report for 1988*, UCRL-50027-88, University of California, Lawrence Livermore National Laboratory, Livermore, California. [SRDB Ref ID: 23035]

Kathren, R. L., Prevo, C. T., and Block, S., 1965, "Angular Dependence of Eastman Type A (NTA) Personnel Monitoring Film," *Health Physics*, volume 11, pp. 1067–1069. [SRDB Ref ID: 6180]

Kay, G. E., 1979, "Progress Report for Activities from October 1, 1978 to December 22, 1978," memorandum to G. E. Tucker, Jr., Sandia National Laboratories, Albuquerque, New Mexico, March 2. [SRDB Ref ID: 20326, p. 5]

Kingsley, W. H., 1968, *Requested Comments on Radiation Exposure Standards*, letter to R. R. Malone (U.S. Atomic Energy Commission), Sandia Corporation, Albuquerque, New Mexico, January 6. [SRDB Ref ID: 23675]

Larsen, B. L., 2003, *Site Environmental Report for 2002, Sandia National Laboratories, California*, SAND2003-8221, Sandia National Laboratories, Livermore, California, June. [SRDB Ref ID: 23350]

Larsen, B. L., 2004, *Site Environmental Report for 2003, Sandia National Laboratories, California*, SAND2004-2169, Sandia National Laboratories, Livermore, California, June. [SRDB Ref ID: 22924]

Larsen, B. L., 2005, *Site Environmental Report for 2004, Sandia National Laboratories, California*, SAND2005-2628, Sandia National Laboratories, Livermore, California. [SRDB Ref ID: 22925]

Larson, J. M., R. J. Harrach, P. E. Althouse, N. A. Bertoldo, A. H. Biermann, R. G. Blake, E. R. Brandstetter, S. L. Brigdon, R. A. Brown, E. Christofferson, K. J. Folks, G. M. Gallegos, L. M. Garcia, T. A. Giesing, A. R. Grayson, L. C. Hall, D. H. MacQueen, S. Mathews, S. R. Peterson, M. J. Taffet, P. J. Tate, R. J. Vellinger, and R. J. Ward, 1999, *Environmental Report 1998*, UCRL-50027-98, H. L. Lentzner, K. S. Rath, and G. S. Siemering, editors, University of California, Lawrence Livermore National Laboratory, Livermore, California, September 1. [SRDB Ref ID: 23045]

Larson, J. M., R. J. Harrach, P. E. Althouse, N. A. Bertoldo, A. H. Biermann, R. G. Blake, E. R. Brandstetter, S. L. Brigdon, R. A. Brown, E. Christofferson, K. J. Folks, G. M. Gallegos, L. M. Garcia, T. A. Giesing, A. R. Grayson, L. C. Hall, D. H. MacQueen, S. Mathews, S. R. Peterson, M. J. Taffet, P. J. Tate, R. J. Vellinger, and R. J. Ward, 1999, *Environmental Report 1998*, *Data Supplement*, UCRL-50027-98, H. L. Lentzner, K. S. Rath, and G. S. Siemering, editors, University of California, Lawrence Livermore National Laboratory, Livermore, California, September 1. [SRDB Ref ID: 140695]

Larson, J. M., A. H. Biermann, R. J. Harrach, P. E. Althouse, N. A. Bertoldo, R. G. Blake, E. R. Brandstetter, S. L. Brigdon, R. A. Brown, E. Christofferson, K. J. Folks, G. M. Gallegos, L. M. Garcia, T. A. Giesing, A. R. Grayson, L. C. Hall, D. H. MacQueen, S. Mathews, S. R. Peterson, M. J. Taffet, P. J. Tate, R. J. Vellinger, R. J. Ward, and R. A. Williams, 2000, *Environmental Report 1999*, UCRL-50027-99, K. S. Rath, N. J. Woods, G. J. Cannon, and N. M. Sanford, editors, University of California, Lawrence Livermore National Laboratory, Livermore, California. [SRDB Ref ID: 23046]

Larson, J. M., A. H. Biermann, R. J. Harrach, P. E. Althouse, N. A. Bertoldo, R. G. Blake, E. R. Brandstetter, S. L. Brigdon, R. A. Brown, E. Christofferson, K. J. Folks, G. M. Gallegos, L. M. Garcia, T. A. Giesing, A. R. Grayson, L. C. Hall, D. H. MacQueen, S. Mathews, S. R. Peterson, M. J. Taffet, P. J. Tate, R. J. Vellinger, R. J. Ward, and R. A. Williams, 2000, *Environmental Report 1999*, *Data Supplement*, UCRL-50027-99, K. S. Rath, N. J. Woods, G. J. Cannon, and N. M. Sanford, editors, University of California, Lawrence Livermore National Laboratory, Livermore, California, September 1. [SRDB Ref ID: 140700]

Lincoln, T. A., and E. D. Gupton, 1958, "Radiation Doses in Diagnostic X-Ray Procedures," Radiology, volume 71, pp. 208–215. [SRDB Ref ID: 11099]

LLNL (Lawrence Livermore National Laboratory), 2004, *Ambient Air Weekly Concentrations from Air Particulate Samples from Various Livermore Locations 2003*, University of California, Lawrence Livermore National Laboratory, Livermore, California. [SRDB Ref ID: 176956]

LLNL (Lawrence Livermore National Laboratory), 2005, *Ambient Air Weekly Concentrations from Air Particulate Samples from Various Livermore Locations 2004*, University of California, Lawrence Livermore National Laboratory, Livermore, California. [SRDB Ref ID: 176949]

LLNL (Lawrence Livermore National Laboratory), 2006, *Ambient Air Weekly Concentrations from Air Particulate Samples from Various Livermore Locations 2005*, University of California, Lawrence Livermore National Laboratory, Livermore, California. [SRDB Ref ID: 176958]

LLNL (Lawrence Livermore National Laboratory), 2007, *Ambient Air Weekly Concentrations from Air Particulate Samples from Various Livermore Locations 2006*, University of California, Lawrence Livermore National Laboratory, Livermore, California. [SRDB Ref ID: 176950]

LLNL (Lawrence Livermore National Laboratory), 2008, *Ambient Air Weekly Concentrations from Air Particulate Samples from the Livermore Perimeter Locations 2007*, University of California, Lawrence Livermore National Laboratory, Livermore, California. [SRDB Ref ID: 176947]

LLNL (Lawrence Livermore National Laboratory), 2009, *Ambient Air Weekly Concentrations from Air Particulate Samples from the Livermore Perimeter Locations 2008,* Lawrence Livermore National Security, Lawrence Livermore National Laboratory, Livermore, California. [SRDB Ref ID: 176926]

LLNL (Lawrence Livermore National Laboratory), 2010, *Ambient Air Weekly Concentrations from Air Particulate Samples from the Livermore Perimeter Locations 2009*, Lawrence Livermore National Security, Lawrence Livermore National Laboratory, Livermore, California. [SRDB Ref ID: 176927]

LLNL (Lawrence Livermore National Laboratory), 2011, *Ambient Air Weekly Concentrations from Air Particulate Samples from the Livermore Perimeter Locations 2010*, Lawrence Livermore National Security, Lawrence Livermore National Laboratory, Livermore, California. [SRDB Ref ID: 176928]

LLNL (Lawrence Livermore National Laboratory), 2012, *Ambient Air Weekly Concentrations from Air Particulate Samples from the Livermore Perimeter Locations 2011,* Lawrence Livermore National Security, Lawrence Livermore National Laboratory, Livermore, California. [SRDB Ref ID: 176929]

LLNL (Lawrence Livermore National Laboratory), 2013, *Ambient Air Weekly Concentrations from Air Particulate Samples from the Livermore Perimeter Locations 2012*, Lawrence Livermore National Security, Lawrence Livermore National Laboratory, Livermore, California. [SRDB Ref ID: 176930]

LLNL (Lawrence Livermore National Laboratory), 2014, *Ambient Air Weekly Concentrations from Air Particulate Samples from the Livermore Perimeter Locations 2013*, Lawrence Livermore National Security, Lawrence Livermore National Laboratory, Livermore, California. [SRDB Ref ID: 176931]

LLNL (Lawrence Livermore National Laboratory), 2015, *Ambient Air Weekly Concentrations from Air Particulate Samples from the Livermore Perimeter Locations 2014*, Lawrence Livermore National Security, Lawrence Livermore National Laboratory, Livermore, California. [SRDB Ref ID: 176932]

LLNL (Lawrence Livermore National Laboratory), 2016, *Ambient Air Weekly Concentrations from Air Particulate Samples from the Livermore Perimeter Locations 2015*, Lawrence Livermore National Security, Lawrence Livermore National Laboratory, Livermore, California. [SRDB Ref ID: 176933]

LLNL (Lawrence Livermore National Laboratory), 2017, *Ambient Air Weekly Concentrations from Air Particulate Samples from the Livermore Perimeter Locations 2016*, Lawrence Livermore National Security, Lawrence Livermore National Laboratory, Livermore, California. [SRDB Ref ID: 176934]

LLNL (Lawrence Livermore National Laboratory), 2018, *Ambient Air Weekly Concentrations from Air Particulate Samples from the Livermore Perimeter Locations 2017*, Lawrence Livermore National Security, Lawrence Livermore National Laboratory, Livermore, California. [SRDB Ref ID: 176936]

Loesch, R. M., 1991, "Laboratory Accreditation of Sandia National Laboratories," memorandum to G. Runkle, U.S. Department of Energy, October 30. [SRDB Ref ID: 19079]

Lovell, P. K., 1966, "Summary of Film Badges Cost Fiscal Year 1966," memorandum to G. L. Rhodes, September 13. [SRDB Ref ID: 23678]

Lovell, P. K., 1980, "Radiation Exposure Incident Involving an X-ray Diffractometer at Sandia Laboratories Livermore," letter to A. R. Sneddon (U. S. Department of Energy, Sandia Area Office), Sandia Laboratories, Livermore, California, February 15. [SRDB Ref ID: 24805]

Lovell, P. K., 1982, "Handling D-38 Contaminated B-83 Parts at SNLL," memorandum to Distribution, Sandia National Laboratories, Livermore, California, February 19. [SRDB Ref ID: 24806]

Lovell, P. K., 1983, "Radiation Dosimetry at Sandia National Laboratories Livermore," memorandum to M. L. Glaze, Sandia National Laboratories, Livermore, California, October 4. [SRDB Ref ID: 24815]

Lovell, P. K., 1984a, "Radiation Control Areas at SNLL," memorandum to W. Bauer, Sandia National Laboratories, Livermore, California, January 31. [SRDB Ref ID: 24803, p. 3]

Lovell, P. K., 1984b, "Radiation Control Areas of SNLL," memorandum to A. R. Willis, Sandia National Laboratories, Livermore, January 31. [SRDB Ref ID: 24803, p. 2]

Lovell, P. K., D. A. Wright, and R. S. Hafner, 1984, *TRL Health Physics Summary, 1979-1983*, Sandia National Laboratories, Livermore, California, June 22. [SRDB Ref ID: 23669, p. 9]

LRL (Lawrence Radiation Laboratory), 1962a, *Environmental Levels of Radioactivity, LRL Livermore - 1961 Annual Report*, University of California, Livermore, California. [SRDB Ref ID: 23473, p. 14]

LRL (Lawrence Radiation Laboratory), 1962b, *Environmental Radiation Levels – Berkeley and Livermore*, University of California, Livermore, California, April. [SRDB Ref ID: 23473, p. 3]

LRL (Lawrence Radiation Laboratory), 1963, *Environmental Levels of Radioactivity, 1962, Lawrence Radiation Laboratory, Livermore*, Livermore, California, March. [SRDB Ref ID: 23493, p. 5]

LRL (Lawrence Radiation Laboratory), 1964, *Environmental Levels of Radioactivity, 1963, Lawrence Radiation Laboratory*, Livermore, California. [SRDB Ref ID: 21081, p. 20]

LRL (Lawrence Radiation Laboratory), 1965, *Environmental Levels of Radioactivity, 1964, Lawrence Radiation Laboratory*, Livermore, California, March. [SRDB Ref ID: 21059, p. 33]

LRL (Lawrence Radiation Laboratory), 1966, *Results of Environmental Radioactivity Sampling Program, Annual Report 1965, Lawrence Radiation Laboratory, Livermore, California*, University of California, Livermore, California. [SRDB Ref ID: 23522]

LRL (Lawrence Radiation Laboratory), 1967, *Results of Environmental Radioactivity Sampling Program, 1966, Lawrence Radiation Laboratory, Livermore, California,* University of California, Livermore, California. [SRDB Ref ID: 23525, p. 14]

LRL (Lawrence Radiation Laboratory), 1968, *Results of Environmental Radioactivity Sampling Program, Annual Report - 1967, Lawrence Radiation Laboratory, Livermore, California*, University of California, Livermore, California. [SRDB Ref ID: 23528]

LRL (Lawrence Radiation Laboratory), 1969, *Results of Environmental Radioactivity Sampling Program, Annual Report 1968, Lawrence Radiation Laboratory, Livermore, California*, University of California, Livermore, California. [SRDB Ref ID: 23530]

LRL (Lawrence Radiation Laboratory), 1970, *Results of Environmental Radioactivity Sampling Program, Annual Report - 1969, Lawrence Radiation Laboratory, Livermore, California*, University of California, Livermore, California. [SRDB Ref ID: 23532]

LRL (Lawrence Radiation Laboratory), 1971, *Results of Environmental Radioactivity Sampling Program Semi-Annual Report, July – December 1970, Lawrence Radiation Laboratory, Livermore, California*, University of California, Livermore, California. [SRDB Ref ID: 23534]

Matthews, S., N. A. Bertoldo, R. A. Brown, C. G. Campbell, S. Cerruti, C. L. Conrado, A. Grayson, H. E. Jones, J. A. Karachewski, G. Kumamoto, J. Larson, D. H. MacQueen, L. Paterson, S. R. Peterson, M. A. Revelli, D. Rueppel, M. J. Taffet, K. Wilson, and J. Woollett, 2007, *Environmental Report 2006*, UCRL-TR-50027-06, D. C. Burke, editor, University of California, Lawrence Livermore National Laboratory, Livermore, California, September 28. [SRDB Ref ID: 140776]

Matthews, S., G. Gallegos, R. Lindee, L. Berg, N. A. Bertoldo, C. G. Campbell, S. Cerruti, J. L. Doman, L. S. Ferry, A. R. Grayson, H. E. Jones, G. Kumamoto, J. Larson, D. H. MacQueen, L. Paterson, M. A. Revelli, M. Ridley, D. Rueppel, A. M. Wegrecki, K. Wilson, and J. Woollett, 2008, *Environmental Report 2007*, UCRL-TR 50027-07, N. J. Woods, editor, University of California, Lawrence Livermore National Laboratory, Livermore, California, August 29. [SRDB Ref ID: 140877]

Meyer, H. E., 1994, *History of Personnel External Dosimetry Program at the Dayton Project and Mound Laboratory, 1946 - 1993*, Volume IV, pp. 171-177, 181-185, Mound Laboratory, Miamisburg, Ohio, March. [SRDB Ref ID: 3288]

Morse, D. H., 1983, *Pelletron 1MV Tandem Accelerator*, SOP No. 851, Sandia National Laboratories, Livermore, California, May 10. [SRDB Ref ID: 23776]

NCRP (National Council on Radiation Protection and Measurements), 1971, *Protection Against Neutron Radiation*, Report 38, Bethesda, Maryland, January 4. [SRDB Ref ID: 11520]

NCRP (National Council on Radiation Protection and Measurements), 1997, *Medical X-Ray, Electron Beam and Gamma-Ray Protection for Energies Up to 50 MeV (Equipment Design, Performance and Use)*, Report 102, Bethesda, Maryland. [SRDB Ref ID: 32467]

Nester, D., 1994, "*ES&H Manual* Chapter 7, Section 6A, 'External Personnel Radiation Dosimetry Program'," memorandum to Distribution, Sandia National Laboratories, Albuquerque, New Mexico, September 28. [SRDB Ref ID: 23654]

NIOSH (National Institute for Occupational Safety and Health), 2007a, *SEC Petition Evaluation Report Sandia National Laboratories – Livermore, Petition SEC-00059*, Office of Compensation Analysis and Support, Cincinnati, Ohio, March 26. [SRDB Ref ID: 175844]

NIOSH (National Institute for Occupational Safety and Health), 2007b, *External Dose Reconstruction Implementation Guideline*, OCAS-IG-001, Rev. 3, Office of Compensation Analysis and Support, Cincinnati, Ohio, November 21. [SRDB Ref ID: 38864]

NIOSH (National Institute for Occupational Safety and Health), 2010, Radiation Exposures Covered for Dose Reconstructions Under Part B of the Energy Employees Occupational Illness Compensation Program Act, DCAS-IG-003, Rev. 1, Division of Compensation Analysis and Support, Cincinnati, Ohio, October 5. [SRDB Ref ID: 88929]

NIOSH (National Institute for Occupational Safety and Health), 2013, *SEC Petition Evaluation Report, Petition SEC-00214*, Division of Compensation Analysis and Support, Cincinnati, Ohio, September 26. [SRDB Ref ID: 129722]

ORAUT (Oak Ridge Associated Universities Team), 2006a, "History of Health Physics, and location of related records, at SNL-CA," documented communication with Sandia National Laboratories employee, Oak Ridge, Tennessee, April 12. [SRDB Ref ID: 23574]

ORAUT (Oak Ridge Associated Universities Team), 2006b, Technical Basis for Conversion from NCRP Report 38 Neutron Quality Factors to ICRP Publication 60 Radiation Weighting Factors for Respective IREP Input Neutron Energy Ranges, ORAUT-OTIB-0055, Rev. 00, Oak Ridge, Tennessee, June 5. [SRDB Ref ID: 29980]

ORAUT (Oak Ridge Associated Universities Team), 2007a, *Oak Ridge National Laboratory – Occupational External Dose*, ORAUT-TKBS-0012-6, Rev. 01, Oak Ridge, Tennessee, September 10. [SRDB Ref ID: 34945]

ORAUT (Oak Ridge Associated Universities Team), 2007b, *Calculation of Dose from Intakes of Special Tritium Compounds,* ORAUT-OTIB-0066, Rev 00, Oak Ridge, Tennessee, April 26. [SRDB Ref ID: 31421]

ORAUT (Oak Ridge Associated Universities Team), 2010a, *Lawrence Livermore National Laboratory – Occupational Medical Dose*, ORAUT-TKBS-0035-3, Rev. 01, Oak Ridge, Tennessee, August 27. [SRDB Ref ID: 86394]

ORAUT (Oak Ridge Associated Universities Team), 2010b, *Lawrence Livermore National Laboratory – Occupational External Dose*, ORAUT-TKBS-0035-6, Rev. 02, Oak Ridge, Tennessee, February 26. [SRDB Ref ID: 79425]

ORAUT (Oak Ridge Associated Universities Team), 2011, Technical Basis Document for the Idaho National Laboratory and Argonne National Laboratory - West – Occupational External Dosimetry, ORAUT-TKBS-0007-6, Rev. 03, Oak Ridge, Tennessee, April 19. [SRDB Ref ID: 94104]

ORAUT (Oak Ridge Associated Universities Team), 2012a, *Dose Reconstruction Method for Chronic Lymphocytic Leukemia*, ORAUT-OTIB-0082, Rev. 00 PC-1, Oak Ridge, Tennessee, December 20. [SRDB Ref ID: 121337]

ORAUT (Oak Ridge Associated Universities Team), 2012b, *Site Profile and Technical Basis Document Development*, ORAUT-PROC-0031, Rev. 04, Oak Ridge, Tennessee, November 5. [SRDB Ref ID: 166849]

ORAUT (Oak Ridge Associated Universities Team), 2013, *Site Profile for Sandia National Laboratories in Albuquerque, New Mexico, and the Tonopah Test Range, Nevada*, ORAUT-TKBS-0037, Rev. 01, Oak Ridge, Tennessee, January 25. [SRDB Ref ID: 122122]

ORAUT (Oak Ridge Associated Universities Team), 2014, *Argonne National Laboratory - East – External Dosimetry*, ORAUT-TKBS-0036-6, Rev. 01, Oak Ridge, Tennessee, October 16. [SRDB Ref ID: 136742]

ORAUT (Oak Ridge Associated Universities Team), 2015, *Hanford Site – Occupational Internal Dose*, ORAUT-TKBS-0006-5, Rev. 06, Oak Ridge, Tennessee, November 16. [SRDB Ref ID: 148938]

ORAUT (Oak Ridge Associated Universities Team), 2016, *Lawrence Livermore National Laboratory – Occupation Internal Dose*, ORAUT-TKBS-0035-5, Rev. 03, Oak Ridge, Tennessee, August 12. [SRDB Ref ID: 159408]

ORAUT (Oak Ridge Associated Universities Team), 2019a, *Technical Information Bulletin: Dose Reconstruction from Occupational Medical X-Ray Procedures*, ORAUT-OTIB-0006, Rev. 06, Oak Ridge, Tennessee, September 27. [SRDB Ref ID: 178310]

ORAUT (Oak Ridge Associated Universities Team), 2019b, *External Dose Reconstruction*, ORAUT-OTIB-0088, Rev 00, Oak Ridge, Tennessee, October 21. [SRDB Ref ID: 178521]

ORAUT (Oak Ridge Associated Universities Team), 2020, *Technical Basis Document for the Lawrence Livermore National Laboratory – Occupational Environmental Dose,* ORAUT-TKBS-0035-4*,* Rev. 02, Oak Ridge, Tennessee, June 9. [SRDB Ref ID: 181348]

Ormond, W. V., 1986, "Radiation Dosimetry at SNLL: Past Present and Future," memorandum to P. E. Brewer, Sandia National Laboratories, Livermore, California, April 22. [SRDB Ref ID: 23896]

Perez-Romo, L., 1994, "Livermore Computer Data – Internal & External Dosimetry," memorandum to G. Nez, Sandia National Laboratories, Albuquerque, New Mexico, July 21. [SRDB Ref ID: 19277]

Peterson, S. R., 2005, *Historical Doses from Tritiated Water and Tritiated Hydrogen Gas Releases to the Atmosphere from Lawrence Livermore National Laboratory (LLNL), Part 2, LLNL Annual Site-specific Data 1953 – 2003*, UCRL-TR-211722, University of California, Lawrence Livermore National Laboratory, Livermore, California, May. [SRDB Ref ID: 26119]

Peterson, S. R., P. E. Althouse, N. A. Bertoldo, R. A. Brown, C. B. Campbell, L. M. Clark, G. M. Gallegos, A. R. Grayson, R. J. Harrach, H. E. Jones, D. H. MacQueen, S. Mathews, B. A. Nisbet, C. D. Noyes, L. Paterson, S. R. Peterson, M. A. Revelli, D. Rueppel, L. Sanchez, M. J. Taffet, P. J. Tate, and K. Wilson, 2005, *Environmental Report 2004*, UCRL-50027-04, N. J. Woods, editor, University of California, Lawrence Livermore National Laboratory, Livermore, California. [SRDB Ref ID: 28169]

Peterson, S. R., D. Armstrong, N. A. Bertoldo, S. Brigdon, R. A. Brown, C. B. Campbell, S. Cerruti, C. L. Conrado, A. R. Grayson, H. E. Jones, J. Karachewski, D. H. MacQueen, S. Mathews, M. A. Revelli, D. Rueppel, L. Sanchez, M. J. Taffet, K. Wilson, and J. Woollett, 2006, *Environmental Report 2005*, UCRL-50027-05, N. J. Woods, editor, University of California, Lawrence Livermore National Laboratory, Livermore, California, September 29. [SRDB Ref ID: 175545]

Potter, C. A., 1994, *Radiation Protection Internal Dosimetry Program Overview*, RPID-00-01, Issue 3, Sandia National Laboratories, Albuquerque, New Mexico, August 10. [SRDB Ref ID: 22093]

Potter, C. A., ca. 1997, *Technical Basis Document for Internal Dosimetry at Sandia National Laboratories*, Rev. 3, Sandia National Laboratories, Albuquerque, New Mexico. [SRDB Ref ID: 23582]

Potter, C. A., F. R. Loudermilk, D. C. Ward, and A. L. Stanley, 1993, *Dosimetry Action Levels*, PRDP-02-06, Issue 2, Sandia National Laboratories, Albuquerque, New Mexico, November 11. [SRDB Ref ID: 19238]

RDC (Radiation Detection Company), 1963, *X-Ray and Cobalt 60 Gamma Ray Calibration of Sandia Corporation Film Badge*, Mountain View, California, March 21. [SRDB Ref ID: 23717]

RDC (Radiation Detection Company), 1969, dosimetry report examples, Mountain View, California. [SRDB Ref ID: 23729]

Rhea, T. A., and E. W. Bradley, 1990, *Documentation of the Sandia National Laboratory Dosimetry Algorithm for the Harshaw 8800/8812 TLD System*, Science Applications International Corporation, Oak Ridge, Tennessee, December. [SRDB Ref ID: 23575]

Rosene, C., H. Jones, R. Blake, M. Buscheck, H. Byrnes, C. Fish, M. Fratanduono, G. Gallegos, D. MacQueen, W. Montemayor, H. Ottaway, L. Paterson, J. Pyon, M. Revelli, K. Swanson, A. Terrill, A. Wegrecki, K. Wilson, and J. Woollett, 2016, *Environmental Report 2015*, UCRL-TR-50027-15, C. Rosene and H. Jones, editors, Lawrence Livermore National Security, Lawrence Livermore National Laboratory, Livermore, California, October 1. [SRDB Ref ID: 175547]

Rosene, C., R. Blake, M. Buscheck, H. Byrnes, S. Diaz, C. Fish, H. Jones, D. MacQueen, W. Montemayor, C. Murphy, C. Noyes, H. Ottaway, L. Paterson, J. Pyon, K. Swanson, C. Vilila, A. Wegrecki, K. Wilson, and J. Woollett, 2017, *Environmental Report 2016*, UCRL-TR-50027-16, C. A. Rosene, editor, Lawrence Livermore National Security, Lawrence Livermore National Laboratory, Livermore, California, October 1. [SRDB Ref ID: 175548]

Rosene, C., R. Blake, E. Brenner, M. Buscheck, H. Byrnes, S. Diaz, C. Fish, H. Jones, D. MacQueen, W. Montemayor, C. Murphy, C. Noyes, H. Ottaway, L. Paterson, K. Swanson, C. Vilila, A. Wegrecki, and K. Wilson, 2018, *Environmental Report 2017*, UCRL-TR-50027-17, C. A. Rosene, editor, Lawrence Livermore National Security, Lawrence Livermore National Laboratory, Livermore, California, October 1. [SRDB Ref ID: 175549]

Rosene, C., M. Abri, M. Buscheck, H. Byrnes, C. Campbell, A. Chan, S. Diaz, T. Jackson, W. Montemayor, C. Murphy, C. Noyes, H. Ottaway, L. Paterson, L. Stephens, M. Taffet, A. Wegrecki, and K. Wilson, 2019, *Environmental Report 2018*, UCRL-TR-50027-18, C. A. Rosene, editor, Lawrence Livermore National Security, Lawrence Livermore National Laboratory, Livermore, California, October 1. [SRDB Ref ID: 178520]

Sanchez, L., P. E. Althouse, N. A. Bertoldo, R. G. Blake, S. L. Brigdon, R. A. Brown, C. G. Campbell, T. Carlsen, E. Christofferson, L. M. Clark, G. M. Gallegos, A. R. Grayson, R. J. Harrach, W. G. Hoppes, H. E. Jones, J. Larson, D. Laycak, D. H. MacQueen, S. Mathews, M. Nelson, L. Paterson, S. R. Peterson, M. A. Revelli, M. J. Taffet, P. J. Tate, R. Ward, R. A. Williams, and K. Wilson, 2003, *Environmental Report 2002*, UCRL-50027-02, N. J. Woods, editor, University of California, Lawrence Livermore National Laboratory, Livermore, California, August 29. [SRDB Ref ID: 28167]

Sanchez, L., P. E. Althouse, N. A. Bertoldo, R. G. Blake, S. L. Brigdon, R. A. Brown, C. G. Campbell, T. Carlsen, E. Christofferson, L. M. Clark, G. M. Gallegos, A. R. Grayson, R. J. Harrach, W. G. Hoppes, H. E. Jones, J. Larson, D. Laycak, D. H. MacQueen, S. Mathews, M. Nelson, L. Paterson, S. R. Peterson, M. A. Revelli, M. J. Taffet, P. J. Tate, R. Ward, R. A. Williams, K. Wilson, and N. J. Woods, 2003, *Environmental Report 2002*, *Data Supplement*, UCRL-50027-02, N. J. Woods, editor, University of California, Lawrence Livermore National Laboratory, Livermore, California, August 29. [SRDB Ref ID: 176961]

Sanchez, L., P. E. Althouse, N. A. Bertoldo, R. G. Blake, S. L. Brigdon, R. A. Brown, E. Christofferson, L. M. Clark, G. M. Gallegos, A. R. Grayson, R. J. Harrach, W. G. Hoppes, H. E. Jones, J. Larson, D. H. MacQueen, S. Mathews, B. A. Nisbet, L. Paterson, S. R. Peterson, M. A. Revelli, D. Rueppel, M. J. Taffet, P. J. Tate, and K. Wilson, 2004, *Environmental Report 2003*, UCRL-50027-03, University of California, Lawrence Livermore National Laboratory, Livermore, California, October 1. [SRDB Ref ID: 28168]

Schwoegler, D. R., J. M. Sims, K. A. Surano, K. C. Lamson, B. K. Balke, and J. C. Steenhoven, 1991, *Environmental Report for 1990*, UCRL-50027-90, University of California, Lawrence Livermore National Laboratory, Livermore, California. [SRDB Ref ID: 26725]

Sebelius, K., 2013, *HHS Designation of Additional Members of the Special Exposure Cohort under the Energy Employees Occupational Illness Compensation Program Act of 2000, Designating a Class of Employees from Sandia National Laboratories – Livermore, California*, U.S. Department of Health and Human Services, Office of the Secretary, Washington, D.C., December 12. [SRDB Ref ID: 129721]

Siegfriedt, K. F., 1989, *1988 Annual Site Environmental Report, Sandia National Laboratories, Livermore, California*, SAND90-8206, Sandia National Laboratories, Livermore, California, May. [SRDB Ref ID: 22993]

Silver, W. J., C. L. Lindeken, J. W. Meadows, W. H. Hutchin, and D. R. McIntyre, 1974, *Environmental Levels of Radioactivity in the Vicinity of the Lawrence Livermore Laboratory, 1973 Annual Report*, UCRL-51547, University of California, Lawrence Livermore Laboratory, Livermore, California, March 4. [SRDB Ref ID: 23912]

Silver, W. J., C. L. Lindeken, J. W. Meadows, E. H. Willes, and D. R. McIntyre, 1975, *Environmental Monitoring at the Lawrence Livermore Laboratory, 1974 Annual Report*, UCRL-50027-74, University of California, Lawrence Livermore Laboratory, Livermore, California. [SRDB Ref ID: 23914]

Silver, W. J., C. L. Lindeken, J. W. Meadows, E. H. Willes, and D. R. McIntyre, 1976, *Environmental Monitoring at the Lawrence Livermore Laboratory, 1975 Annual Report*, UCRL-50027-75, University of California, Lawrence Livermore Laboratory, Livermore, California, April 15. [SRDB Ref ID: 23916]

Silver, W. J., C. L. Lindeken, K. M. Wong, E. H. Willes, and J. H. White, 1977, *Environmental Monitoring at the Lawrence Livermore Laboratory, 1976 Annual Report*, UCRL-50027-76, University of California, Lawrence Livermore Laboratory, Livermore, California, March 11. [SRDB Ref ID: 14834]

Silver, W. J., C. L. Lindeken, K. M. Wong, E. H. Willes, and J. H. White, 1978, *Environmental Monitoring at the Lawrence Livermore Laboratory, 1977 Annual Report*, UCRL-50027-77, University of California, Lawrence Livermore Laboratory, Livermore, California, March 11. [SRDB Ref ID: 23394]

Silver, W. J., C. L. Lindeken, K. M. Wong, A. Conover, and J. H. White, 1979, *Environmental Monitoring at the Lawrence Livermore Laboratory, 1978 Annual Report*, UCRL-50027-78, University of California, Lawrence Livermore Laboratory, Livermore, California, March 11. [SRDB Ref ID: 23396]

Silver, W. J., C. L. Lindeken, J. H. White, and R. W. Buddemeier, 1980, *Environmental Monitoring at the Lawrence Livermore Laboratory, 1979 Annual Report*, UCRL-50027-79, University of California, Lawrence Livermore Laboratory, Livermore, California, April 25. [SRDB Ref ID: 23033]

SNL (Sandia National Laboratories), 1958–1961, miscellaneous dosimetry details 1958–1961, Livermore, California. [SRDB Ref ID: 23727]

SNL (Sandia National Laboratories), 1958–1978, summary of whole-body radiation exposures to ionizing (or external penetrating) radiation accumulated during the year, 1958–1978, Livermore, California. [SRDB Ref ID: 24827]

SNL (Sandia National Laboratories), 1960–1983, external radiation exposure incidents, 1960–1983, Livermore, California. [SRDB Ref ID: 23665]

SNL (Sandia National Laboratories), 1961–1962, external dosimetry data (1961–1962), Livermore, California. [SRDB Ref ID: 23720]

SNL (Sandia National Laboratories), 1962, dosimetry program suppliers (1962), Livermore, California. [SRDB Ref ID: 23724]

SNL (Sandia National Laboratories), 1963, miscellaneous dosimetry program details, 1963, Livermore, California. [SRDB Ref ID: 23700]

SNL (Sandia National Laboratories), 1964, miscellaneous dosimetry program details, 1964, Livermore, California. [SRDB Ref ID: 23689]

SNL (Sandia National Laboratories), 1965–1990, uranium bioassay results 1965-1990, Livermore, California. [SRDB Ref ID: 23658]

SNL (Sandia National Laboratories), 1975–1977, sample urinalysis tests for tellurium and uranium and other lab tests, Livermore, California. [SRDB Ref ID: 22862]

SNL (Sandia National Laboratories), 1980–1984, termination occupational exposure reports (1975–1984), Sandia National Laboratories, Livermore, California. [SRDB Ref ID: 24828]

SNL (Sandia National Laboratories), 1982, *Sandia National Laboratories Livermore, Environmental Summary, Calendar Year 1982*, Livermore, California. [SRDB Ref ID: 23132]

SNL (Sandia National Laboratories), 1983, *Sandia National Laboratories Livermore, Environmental Summary, Calendar Year 1983*, Livermore, California. [SRDB Ref ID: 23130]

SNL (Sandia National Laboratories), 1984, *Sandia National Laboratories Livermore, Environmental Summary, Calendar Year 1984*, Livermore, California. [SRDB Ref ID: 23129]

SNL (Sandia National Laboratories), 1989, *Machining Depleted Uranium Metal*, SNLL-SOP 1066, Rev. C, Livermore, California, October 1. [SRDB Ref ID: 23733]

SNL (Sandia National Laboratories), 1990, *Safe Operating Procedure for the use of a Neutron/X-Ray Generator,* SOP No. 733, Rev. B, Livermore, California, February 1. [SRDB Ref ID: 23744]

SNL (Sandia National Laboratories), 1991a, *Safe Operating Procedure No. 757, Tritium Research Laboratory, Uranium Tritide Bed*, Livermore, California, February 26. [SRDB Ref ID: 23774]

SNL (Sandia National Laboratories), 1991b, *Safe Operating Procedure No. 709, Tritium Research Laboratory, Building 968*, Livermore, California, April 19. [SRDB Ref ID: 23740]

SNL (Sandia National Laboratories), 1991c, *Safe Operating Procedure for 700/200 KeV Positive Ion Accelerator System,* SOP No. 382, Livermore, California, August 7. [SRDB Ref ID: 23743]

SNL (Sandia National Laboratories), 1992, *Performance Indicator Report, 1st Quarter CY 1992*, Albuquerque, New Mexico. [SRDB Ref ID: 18964]

SNL (Sandia National Laboratories), 1993a, chain-of-custody records, Albuquerque, New Mexico. [SRDB Ref ID: 19585]

SNL (Sandia National Laboratories), 1993b, miscellaneous uranium bioassay documents, Albuquerque, New Mexico. [SRDB Ref ID: 19583]

SNL (Sandia National Laboratories), 1993c, “Non-Returned Dosimeter Notice,” memorandum to P. Boehme (U.S. Department of Energy), Albuquerque, New Mexico, March 5. [SRDB Ref ID: 20510]

SNL (Sandia National Laboratories), 1995, *Work Area Dosimetry Processing*, RPXD-30-03, Issue 4, Albuquerque, New Mexico. [SRDB Ref ID: 19096]

SNL (Sandia National Laboratories), 1996a, TLD calibration forms and records of irradiation, Albuquerque, New Mexico. [SRDB Ref ID: 19543]

SNL (Sandia National Laboratories), 1996b, card reader calibration checklist and accompanying records, Albuquerque, New Mexico. [SRDB Ref ID: 22309]

SNL (Sandia National Laboratories), 1997, “Monthly ALARA Radiation Dosimetry Report,” memorandum to Distribution, Albuquerque, New Mexico, December 31. [SRDB Ref ID: 19253]

SNL (Sandia National Laboratories), undated a, *Sandia National Laboratories Livermore Program to Reduce Radiation Exposure to As Low As Reasonably Achievable*, Livermore, California. [SRDB Ref ID: 23651]

SNL (Sandia National Laboratories), undated b, *Radiation Dosimeters*, Hazards Control Bulletin, Sandia National Laboratories, Livermore, California. [SRDB Ref ID: 23652, p. 4]

SNL (Sandia National Laboratories), undated c, *SNL Livermore External Dosimetry Records – Prior to 1973, IN MREMS*, Livermore, California. [SRDB Ref ID: 24816]

Stanley, A. L., 1987a, "3318 Progress Summary, October - December, 1986," memorandum to W. D. Burnett, Sandia National Laboratories, Albuquerque, New Mexico, January 8. [SRDB Ref ID: 20326, p. 4]

Stanley, A. L., 1987b, "Progress Report, April - June 1987," memorandum to W. D. Burnett, Sandia National Laboratories, Albuquerque, New Mexico, July 28. [SRDB Ref ID: 20326, p. 3]

Stanley, A. L., 1987c, "Third Quarter Progress Report, July-September, 1987," memorandum to W. D. Burnett, Sandia National Laboratories, Albuquerque, New Mexico, October 27. [SRDB Ref ID: 20326, p. 2]

Stanley, A. L., 1991, "Basis for Wearing Only One Dosimeter," memorandum to N. R. Ortiz, Sandia National Laboratories, Albuquerque, New Mexico, April 22. [SRDB Ref ID: 18275]

Thompson, B. C., 1991, *Sandia National Laboratories Radiation Protection Overview Program*, Sandia National Laboratories, January 24. [SRDB Ref ID: 19284]

Tipton, W. J., 1977, *An Aerial Radiological Survey of the Lawrence Livermore Laboratory (Livermore, California), Date of Survey: August 1975*, EGG-1183-1693, EG&G/Energy Measurements, Las Vegas, Nevada, October. [SRDB Ref ID: 34498]

Tucker, G. E. Jr., 1977a, "Division 3313 Progress Report, Second Quarter 1977," memorandum to W. H. Kingsley, Sandia Laboratories, Albuquerque, New Mexico, July 6. [SRDB Ref ID: 20326, p. 22]

Tucker, G. E. Jr., 1977b, "Division 3313 Progress Report, Third Quarter," memorandum to W. H. Kingsley, Sandia Laboratories, Albuquerque, New Mexico, October 13. [SRDB Ref ID: 20326, p. 15]

Tucker, G. E. Jr., 1978, "Division 3313 Progress Report - 1977 Fourth Quarter," memorandum to W. D. Burnett, Sandia Laboratories, Albuquerque, New Mexico, February 6. [SRDB Ref ID: 20326, p. 7]

Toy, A. J. , C. L. Lindeken, K. S. Griggs, and R. W. Buddemeier, 1981, *Environmental Monitoring at the Lawrence Livermore National Laboratory: 1980 Annual Report*, UCRL-50027-80, University of California, Lawrence Livermore National Laboratory, Livermore, California, April 15. [SRDB Ref ID: 14835]

Turner, J. E., 1996, *Atoms, Radiation, and Radiation Protection, 2nd Edition*, John Wiley & Sons, New York, New York. [SRDB Ref ID: 176612]

Ullrich, R. A., 2003, *Cold War Context Statement, Sandia National Laboratories, California Site*, SAND2003-0112, Sandia National Laboratories, Albuquerque, New Mexico, January. [SRDB Ref ID: 22926]

Walker, S., 1995, "Dose Assignment for [Privacy Act information]," memorandum to L. Lippert, Sandia National Laboratories, Albuquerque, New Mexico, June 22. [SRDB Ref ID: 18285]

Walker, S., 1996, "Environmental Background Accumulation Rates for SNL-NM, SNL-CA, and SNL-NV," memorandum to DPR/REP Files, Sandia Corporation, Sandia National Laboratories, Albuquerque, New Mexico, December 5. [SRDB Ref ID: 19251]

Walker, S., 1997a, "Interim Processing Steps for EXTRAD and Model 8807 Dosimeters," memorandum to L. Garcia-Larkin and J. Zamora, Sandia Corporation, Sandia National Laboratories, Albuquerque, New Mexico, August 11. [SRDB Ref ID: 19247]

Walker, S., 1997b, "Lens of the Eye Dose Equivalent (LDE) Monitoring at SNL," memorandum to PCS/TRK Files, Sandia Corporation, Sandia National Laboratories, Albuquerque, New Mexico, February 3. [SRDB Ref ID: 19249]

Walker, S., 1997c, "SANDOS Background Subtraction Problem," memorandum to PCS/TRK Files, Sandia Corporation, Sandia National Laboratories, Albuquerque, New Mexico, April 8. [SRDB Ref ID: 19248]

Walker, S. W., F. R. Loudermilk, and D. J. Thompson, 1997, *Lower Limit of Detection (LLD) for the Harshaw 8802 TLD*, Sandia National Laboratories, Albuquerque, New Mexico, March 5. [SRDB Ref ID: 23577, p. 194]

Wall, W. R., 1981, *Tritium Control and Accountability Instructions*, SAND80-8057, Sandia National Laboratories, Livermore, California, March. [SRDB Ref ID: 22994, p. 302]

Wallace, S. A., 1988, "Current Status of 1985 Headquarters (HQ) Nuclear Facilities Appraisal (Ref. Audit E431)," memorandum to W. V. Ormand, Sandia National Laboratories, Albuquerque, New Mexico, September 9. [SRDB Ref ID: 23585]

Ward, D. C., 1992, *Special Dosimetry Program*, PRDP-00-03, Issue 01, Sandia National Laboratories, Albuquerque, New Mexico, October 23. [SRDB Ref ID: 18278]

Ward, D. C., 1994, *External Dosimetry Program*, PRDP-00-01, Issue 05, Sandia National Laboratories, Albuquerque, New Mexico, March 3. [SRDB Ref ID: 19237]

Willhoite, S. B., 1979, "Determination of Gamma and Neutron Yearly Doses at the Building 212 Bus Stop," December 12. [SRDB Ref ID: 15066]

Wright, D., 1993, "History of Radiation Dosimetry at SNL-CA as Remembered by D.A. Wright, 8641," memorandum to L. Perez, Sandia National Laboratories, Livermore, California, June 1. [SRDB Ref ID: 24811]

Wright, D. A., 1979a, "Sandia Livermore's Bioassay Program from Depleted Uranium," memorandum to Distribution, Sandia National Laboratories, May 14. [SRDB Ref ID: 24813]

Wright, D. A., 1979b, "Radiation Workers at SLL," memorandum to H. M. Patterson, Sandia Laboratories, December 20. [SRDB Ref ID: 24824]

Wright, D. A., 1998, untitled memorandum to D. Miller (U.S. Department of Energy, Albuquerque Operations Office), Sandia National Laboratories, Livermore, California, February 19. [SRDB Ref ID: 23655]

Wright, D. A., 1981a, *Tritium Research Laboratory Safety Analysis Report*, SAND81-8234, Sandia National Laboratories, Livermore, California, August. [SRDB Ref ID: 22994]

Wright, D. A., 1981b, "Radiation Dosimetry at Sandia National Laboratories Livermore," memorandum to P. K. Lovell, Sandia National Laboratories, November 6. [SRDB Ref ID: 24820]

Wright, D. A., and R. S. Hafner, 1981, *TRL Health Physics Summary, First Quarter, 1981*, memorandum to Distribution, Sandia National Laboratories, April 20. [SRDB Ref ID: 23669, p. 64]

GLOSSARY

alpha radiation
Positively charged particle emitted from the nuclei of some radioactive elements. An alpha particle consists of two neutrons and two protons (a helium nucleus) and has an electrostatic charge of +2.

becquerel (Bq)
International System unit of radioactivity equal to 1 disintegration per second; 1 curie equals 37 billion (3.7×10^{10}) Bq.

beta radiation
Charged particle emitted from some radioactive elements with a mass equal to 1/1,837 that of a proton. A negatively charged beta particle is identical to an electron. A positively charged beta particle is a positron.

curie (Ci)
Traditional unit of radioactivity equal to 37 billion (3.7×10^{10}) becquerels, which is approximately equal to the activity of 1 gram of pure ^{226}Ra.

depleted uranium (DU)
Uranium with a percentage of ^{235}U lower than the 0.7% found in natural uranium.

dosimeter
Device that measures the quantity of received radiation, usually a holder with radiation-absorbing filters and radiation-sensitive inserts packaged to provide a record of absorbed dose received by an individual. See *film dosimeter* and *thermoluminescent dosimeter*.

dosimetry
Measurement and calculation of internal and external radiation doses.

dosimetry system
System for assessment of received radiation dose. This includes the fabrication, assignment, and processing of external dosimeters, and/or the collection and analysis of bioassay samples, and the interpretation and documentation of the results.

exposure
(1) In general, the act of being exposed to ionizing radiation. (2) Measure of the ionization produced by X- and gamma-ray photons in air in units of roentgens.

film
(1) In the context of external dosimetry, radiation-sensitive photographic film in a light-tight wrapping. See *film dosimeter*. (2) X-ray film.

film dosimeter
Package of film for measurement of ionizing radiation exposure for personnel monitoring purposes. A film dosimeter can contain two or three films of different sensitivities, and it can contain one or more filters that shield parts of the film from certain types of radiation. When developed, the film has an image caused by radiation measurable with an optical densitometer. Also called film badge.

fission

Splitting of the nucleus of an atom (usually of a heavy element) into at least two other nuclei and the release of a relatively large amount of energy. This transformation usually releases two or three neutrons.

gamma radiation

Electromagnetic radiation (photons) of short wavelength and high energy (10 kiloelectron-volts to 9 megaelectron-volts) that originates in atomic nuclei and accompanies many nuclear reactions (e.g., fission, radioactive decay, and neutron capture). Gamma photons are identical to X-ray photons of high energy; the difference is that X-rays do not originate in the nucleus.

gamma ray, particle, or photon (γ)

See *gamma radiation*.

ionizing radiation

Radiation of high enough energy to remove an electron from a struck atom and leave behind a positively charged ion. High enough doses of ionizing radiation can cause cellular damage. Ionizing particles include alpha particles, beta particles, gamma rays, X-rays, neutrons, high-speed electrons, high-speed protons, photoelectrons, Compton electrons, positron/negatron pairs from photon radiation, and scattered nuclei from fast neutrons. See *gamma radiation*, *neutron radiation*, and *X-ray radiation*.

isotope

One of two or more atoms of a particular element that have the same number of protons (atomic number) but different numbers of neutrons in their nuclei (e.g., ^{234}U, ^{235}U, and ^{238}U). Isotopes have very nearly the same chemical properties.

neutron

Basic nucleic particle that is electrically neutral with mass slightly greater than that of a proton. There are neutrons in the nuclei of every atom heavier than normal hydrogen.

neutron film dosimeter

Film dosimeter with a nuclear track emulsion, type A, film packet.

neutron radiation

Radiation that consists of free neutrons unattached to other subatomic particles emitted from a decaying radionuclide. Neutron radiation can cause further fission in fissionable material such as the chain reactions in nuclear reactors, and nonradioactive nuclides can become radioactive by absorbing free neutrons. See *neutron*.

nuclide

Stable or unstable isotope of any element. Nuclide relates to the atomic mass, which is the sum of the number of protons and neutrons in the nucleus of an atom. A radionuclide is an unstable nuclide.

photon radiation

Electromagnetic radiation that consists of quanta of energy (photons) from radiofrequency waves to gamma rays.

radiation

Subatomic particles and electromagnetic rays (photons) with kinetic energy that interact with matter through various mechanisms that involve energy transfer. See *ionizing radiation*.

radioactive
Of, caused by, or exhibiting radioactivity.

radioactivity
Property possessed by some elements (e.g., uranium) or isotopes (e.g., ^{14}C) of spontaneously emitting energetic particles (electrons or alpha particles) by the disintegration of their atomic nuclei. See *radionuclide*.

radionuclide
Radioactive nuclide. See *radioactive* and *nuclide*.

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

thermoluminescence
Property that causes a material to emit light as a result of heat.

thermoluminescent dosimeter (TLD)
Device for measuring radiation dose that consists of a holder containing solid chips of material that, when heated, release the stored energy as light. The measurement of this light provides a measurement of absorbed dose. TLDs replaced film dosimeters at essentially all U.S. Department of Energy sites beginning in the 1960s.

X-ray radiation
Electromagnetic radiation (photons) produced by bombardment of atoms by accelerated particles. X-rays are produced by various mechanisms including bremsstrahlung and electron shell transitions within atoms (characteristic X-rays). Once formed, there is no difference between X-rays and gamma rays, but gamma photons originate inside the nucleus of an atom.

ATTACHMENT A
SUMMARY OF ACTIVITIES AT SITE BUILDINGS

Table A-1. Summary of activities by building.[a]

Building number	Building use	Radiological activities	Dates of use	Nuclides	Comments
904	Auditorium	None	1980s–present	None	None
905	Offices	None	1980s–present	None	None
906	Combustion Laboratory Research	None	1980s–present	None	None
907	Equipment room	None	1980s–present	None	None
910	Weapons Laboratory Facility	Neutron detection	Unknown	Unknown	Used to design, assemble, test, calibrate, and repair neutron detectors
911	Administration	None	None	None	None
912	Administration, computers	None	1958–present	None	None
913	Test assembly, machine shop, plating, metallography, tritium high-velocity air hoods	Tritium storage studies, U machining	1976–1998	H-3, U-238	None
914	Test laboratories	Radiflo, nondestructive testing, U machining	Unknown	Kr-85, beta sources, U-238	No radiological work for about 15 years
915	New building, office space	None	None	None	None
916	Mostly light chemistry laboratories, previously a warehouse, Ar gloveboxes	E–microscopes, accelerators, various small sources, H-2 storage tests	Unknown	700 keV, 1 MeV, U-238	Sealed sources
917	Cylinder storage	None	None	None	None
918	Raw stock	U-machining	Unknown	U-238	Deconstructed in the late 1980s
920	Office space	None	1977–present	None	None
921	Decommissioned in 1980	Radiological material storage and decontamination of Nevada Test Site test units	Unknown	U-238, trace Pu-239, and mixed fission products	Became Building 9632 in 1980 (Carter 2009)
922	Office space	None	None	None	None
923	Radiography Laboratory	Radiography operations, X-ray machines	Unknown	Co-60 and Ir-192; X-ray machines, Cf-252	Converted to records storage in early 1990s
924 Mo	Mobile counting laboratory	Unknown	Unknown	Unknown	Health Physics laboratory moved to Building 973
925	Health services	None	None	None	None

ATTACHMENT A
SUMMARY OF ACTIVITIES AT SITE BUILDINGS (continued)

Building number	Building use	Radiological activities	Dates of use	Nuclides	Comments
927	Radiological Material Storage	Warehouse and vault	Unknown	U-238, natural thorium	None
928	Shipping and receiving	None	None	None	None
929	Office space	None	None	None	None
940	Office space	None	None	None	None
941	Light mechanical, electrical, chemical laboratories	Radiography	Unknown	X-ray U-238, beta sources	Sealed sources
942	Light mechanical, electrical, chemical laboratories	None	None	None	None
943	Plating operations	None	None	None	None
955	Environmental Test Facility	Environmental testing of various test units	Unknown	U-238 metal	None
956	Vibration Test Facility	Environmental testing of various test units	Unknown	U-238 metal	None
960	Offices	None	None	None	None
961	Radiological and mixed waste storage and packaging	Storage and packaging	Unknown	H-3, U-238	None
9611	Chemical waste storage	None	None	None	None
963	Maintenance Facilities	None	None	None	None
964	Security	None	None	None	None
966	High Pressure Gas Dynamics Test Facility	None	None	None	None
967	Office	None	None	None	None
968	TRL	Tritium research	1976–1989	H-3, U-238 beds	Decommissioned in 1996, converted to biotech
969	Former TRL waste storage	Radiological waste storage for site	1976–1989	H-3, U-238	Converted to shop and storage when TRL decommissioned
970	Welding shop	None	None	None	None
972	Centrifuge	Test package centrifuge, penetrator studies	Unknown	U-238	None
973	Environment, safety, and health laboratories	None	None	None	None
974	Explosives test tanks	Neutron generator tests	Unknown	H-3	None
976	Four test cells for high press work	H-2 storage tests	Unknown	U-238	None
978	Flight test unit testing	Mass properties tests	Unknown	U-238	None
979	H-2 storage, research and development	Unknown	Unknown	U-238	Three Ar gloveboxes, two contaminated machines

ATTACHMENT A
SUMMARY OF ACTIVITIES AT SITE BUILDINGS (continued)

Building number	Building use	Radiological activities	Dates of use	Nuclides	Comments
983	Test cells, flight test assembly	Unknown	Unknown	U-238	None
Explosives Storage Area	Magazines, explosives storage	Unknown	Unknown	H-3	None

a. Sources: DOE (1982); Wright (1981a, 2006).

ATTACHMENT B
DOSIMETRY PROGRAM ADMINISTRATIVE DOCUMENTATION EXAMPLES

LIST OF FIGURES

FIGURE **TITLE** **PAGE**

B-1 Example external dosimetry history records (output from SANDOS) 100
B-2 Example nonroutine dosimeter evaluation form for special radiation work case (potential neutron exposures) 101
B-3 Example nonroutine dosimeter evaluation form for special radiation work case (potential neutron exposures) 102
B-4 Example unreturned dosimeter investigation report 103
B-5 Example unreturned dosimeter questionnaire follow-up letter 104
B-6 Example portion of unreturned dosimeter questionnaire showing various codes used by the Personnel Dosimetry Division 105
B-7 Work Area Radiation Dosimetry Request Form 106
B-8 Example work area radiation dosimetry results report 107

ATTACHMENT B
DOSIMETRY PROGRAM ADMINISTRATIVE DOCUMENTATION EXAMPLES (continued)

Date: 11/15/95 ********** PRIVATE **********

Name.....: [redacted] Contact Org.....: 88613 Statu

Dates of Coverage		DDE	Skin	Extrem.	Eyes	Deep	Shallow	Neutron
Fourth Quarter	1989	0.000	0.000			0.000	0.000	
Total for Year	1989	0.000	0.000			0.000	0.000	
First Quarter	1990	0.000	0.000			0.000	0.000	
Second Quarter	1990	0.000	0.000			0.000	0.000	
Third Quarter	1990	0.000	0.000			0.000	0.000	
Fourth Quarter	1990	0.000	0.000			0.000	0.000	0.000
Total for Year	1990	0.000	0.000			0.000	0.000	0.000
First Quarter	1991	0.000	0.000			0.000	0.000	0.000
Second Quarter	1991	0.000	0.000			0.000	0.000	0.000
Third Quarter	1991	0.000	0.000			0.000	0.000	0.000
Fourth Quarter	1991	0.000	0.011			0.000	0.011	0.000
Total for Year	1991	0.000	0.011			0.000	0.011	0.000
First Quarter	1992	0.000	0.000			0.000	0.000	0.000
Second Quarter	1992	0.010	0.010			0.010	0.010	0.000
Third Quarter	1992	0.000	0.000			0.000	0.000	0.000
Fourth Quarter	1992	0.000	0.000			0.000	0.000	0.000
Total for Year	1992	0.010	0.010			0.010	0.010	0.000
First Quarter	1993	0.000	0.000			0.000	0.000	0.000
Second Quarter	1993	0.000	0.000			0.000	0.000	0.000
Third Quarter	1993	0.000	0.000			0.000	0.000	0.000
Fourth Quarter	1993	0.000	0.000			0.000	0.000	0.000
Total for Year	1993	0.000	0.000			0.000	0.000	0.000
First Quarter	1994	0.000	0.000			0.000	0.000	0.000
Second Quarter	1994	0.000	0.000			0.000	0.000	0.000
Third Quarter	1994	0.000	0.000			0.000	0.000	0.000
Fourth Quarter	1994	0.000	0.000			0.000	0.000	0.000
Total for Year	1994	0.000	0.000			0.000	0.000	0.000
First Quarter	1995	0.000	0.000			0.000	0.000	0.000
Second Quarter	1995	0.000	0.000			0.000	0.000	0.000
Total for Year	1995	0.000	0.000			0.000	0.000	0.000

******** End of Report ********

Note: Year 0000 is for all years prior to 1987.

Figure B-1. Example external dosimetry history records (output from SANDOS).

ATTACHMENT B
DOSIMETRY PROGRAM ADMINISTRATIVE DOCUMENTATION EXAMPLES (continued)

NON-ROUTINE PERSONNEL DOSIMETER EVALUATION

Page No. 1 VER340325

REASON Possible exposure

☐ High Readout ☒ Other (specify) Possible Exposure (to neutrons)

☒ Special Evaluation Requested by: Tom Laiche (Name) 6/1/95 (Date)

USER INFORMATION

Name: [redacted] Social Security Number: [redacted]

Neutron Code: 90 Assigned Org. (at time of issue): 7714 Mail Stop:

LOCATION - Room: Worksite Code: SA

Additional location information, if available: QUARTERLY ISSUED DOSIMETRY USED FOR NON-ROUTINE WORK. NEUTRON DOE STILL VALID DUE TO SHIELDING

ASSIGNED Use Dates: From 6/1/95 to 6/30/95 ACTUAL Use Dates: From 6/1/95 to 6/1/95

DOSIMETER INFORMATION

Dosimeter Number: [redacted] File Name: [redacted] Annual Date: 5/26/95

Read Date: 6/1/95 Background Days:

READOUT (gu) - Element #1: 2.902 Element #2: 3.595 Element #3: 1.646 Element #4: 38.307

BACKGROUND - (If applicable)

BACKGROUND RATE (gu/day)	ENVIRONMENTAL BKG (gu)	SYSTEM BKG (gu)	6/6/95 TOTAL BKG (gu)
Element #1	Element #1 0.980	Element #1 -0.980 (subd)	Element #1
Element #2	Element #2 0.980	Element #2	Element #2
Element #3	Element #3 1.120	Element #3	Element #3
Element #4	Element #4 1.540	Element #4	Element #4

TRIP CONTROL INFORMATION - (If applicable) N/A

File Name:

Annual Date:

Read Date:

GROSS AVERAGE READOUT (gu)

Element #1 Element #2

Element #3 Element #4

Figure B-2. Example nonroutine dosimeter evaluation form for special radiation work case (potential neutron exposures).

ATTACHMENT B
DOSIMETRY PROGRAM ADMINISTRATIVE DOCUMENTATION EXAMPLES (continued)

Page No. 2 YE8540203

CHECKLIST

TO DO		DONE	TO DO		DONE
☐	Additional QC Cards Read		☒	Copy Glow Curves of Card Read, ~~Re-Read~~	SW
☒	Visually Inspect Card(s)	SW	☒	Copy TLD Card Reader Daily Calibration	SW
☐	~~Reread~~ Card(s)		☐	Other (specify)	
☐	Generate ECC(s) (if directed by Dosimetry Staff Leader)				

Comments: CARD & GLOW CURVE INSPECTIONS WERE SATISFACTORY

Work Performed By: S. WALKER (Name) 6/2/95 (Date)

DOSE - (rem)

DEEP	SHALLOW	NEUTRON
0.000	0.000	0.000

Comments: NEUTRON CODE NOT CHANGED SINCE INDIVIDUAL WAS STANDING WELL OFF FROM ^{252}Cf SOURCE, behind a moderated shield.

Dose Calculated By: SCOTTIE WALKER (Name) 6/2/95 (Date)

CONTACT REQUESTOR - (If applicable)

Name	Org.	Mailstop	Date	Time
TOM LAICHE	7714		6/5/95	0905

Phone Number Where Requestor Can Be Reached or Message Left:

DOSIMETRY PROJECT LEADER ACTIONS

(Concurrence/~~Non-Concurrence~~) Comments: 7714 personnel informed of the need to request special dosimetry when working on jobs outside their normal scope.

SCOTTIE WALKER (Dosimetry Project Leader) Scottie Walker (Signature of Dosimetry Project Leader) 6/6/95 (Date)

ACTION TAKEN - (Section to be completed by 7715 personnel ONLY)

Brief Explanation (if necessary): No neutron code change was warranted since the individual was located behind a water moderator.

Dose Assignment Entered into SANDOS By: S WALKER IC Code(s): (If any) TE 207 Date: 6/6/95

Figure B-3. Example nonroutine dosimeter evaluation form for special radiation work case (potential neutron exposures).

ATTACHMENT B
DOSIMETRY PROGRAM ADMINISTRATIVE DOCUMENTATION EXAMPLES (continued)

Report Date: 11/15/95 — PRIVATE — RETURN TO: MS 065

Non-Returned Dosimeter Investigation Report

CUSTOMER DATA

Dosimeter No. [redacted] Assigned To: [redacted] SS No.: [redacted]

Dosimeter Type: TLD Whole Body Issue Date: 07/01/95 Due Date: 09/30/95 Current Org.: 08613

Assigned Org During Issue Period in Question: 08613 Period of Coverage from 07/01/95 to 09/30/95

Company Name (if individual is not a Sandia employee): JOHNSON CONTROLS

REASON FOR INVESTIGATIO

LOST DOSIMETER

INFORMATION ONLY

EMPLOYEE'S PREVIOUS RADIATION EXPOSURE HISTORY

Dose for Prior Period:	04/01/95 to 06/30/95	is 0.0	deep	0.0	shallow	0.0	neutron rem
Dose for Current Year-to-Date:	1995	is 0.0	deep	0.0	shallow	0.0	neutron rem
Dose for Previous Year:	1994	is 0.0	deep	0.0	shallow	0.0	neutron rem

THE EXPOSURE OF PERSONNEL WORKING WITH EMPLOYEE DURING THE PERIOD IN QUESTION

Name of Employee	Social Security No.	Dates of Exposure	Dose (rem)
			____ deep ____ shallow ____ neutron
			____ deep ____ shallow ____ neutron
			____ deep ____ shallow ____ neutron

DOSE ESTIMATE

The BodyDose Estimate for the period 07/01/95 to 09/30/95, is 0.0 deep 0.0 shallow 0.0 neutron rem

The Estimate is Based on: [X] Previous History [ ] Exposure of Other Personnel

[ ] Other _____

DOSE ESTIMATE APPROVALS

If dose estimate is not acceptable, list reason(s) on a separate sheet and return all correspondence for further consideration.

I have reviewed the dose estimate for the period 07/01/95 to 09/30/95 and agreed th

0.0 deep 0.0 shallow 0.0 neutron (rem) is the Body dose that should be recorded for this period.

▶ Employee Signature:	[redacted]	Org: 7613	Date: 11-22-95	
▶ Department Manager Signature:	(Department or Above)	Org: 8613	Date: 11-29-95	
▶ Health Physicist Signature:	N/A (Required only if assigned dose is 0.100 (rem) or greater)	Org:	Date:	
▶ Radiation Dosimetry Signature:		Org: 7715	Date: 12/4/95	

ACTION TAKEN (Shaded area to be completed by 721 only following dose estimate approvals) Assigned Badge N: 007142

Reviewed by Dosimetry Project Leader: [signature] Remarks Code: [illegible] Entry Date: 12/7/95 Entered By: [signature] Filed By: [signature]

Figure B-4. Example unreturned dosimeter investigation report.

ATTACHMENT B
DOSIMETRY PROGRAM ADMINISTRATIVE DOCUMENTATION EXAMPLES (continued)

Sandia National Laboratories

Albuquerque, New Mexico 87185

date: 11/15/95

to: Manager, 08613

from: Radiation Protection Measurements Dept. 7715, MS 0651

subject: Non-Returned Dosimeter Questionnaire - Follow-Up

reference: [redacted] 08613 SS#: [redacted]

Dosimeter Use Period: from 07/01/95 to 09/30/95

Assigned Org. at Issue: 08613 Current Org.: 08613

Dosimeter No.: [redacted] Dosimeter Due Date: 10/14/95

Thank you for your cooperation on the Non-Returned Dosimeter Questionnaire. On the reverse side is the follow-up External Dosimetry Investigation Report. This report is based, in part, on the information you provided on the Non-Returned Dosimeter Questionnaire and is intended to facilitate your investigation. It is the responsibility of the Supervisor to complete the investigation, obtain the required signatures (including the appropriate Health Physicist), and return the completed report to the Dosimetry Distribution Center, Department 7715. Refer to the listing below to obtain the appropriate Health Physicist signature. If the investigation report is not returned within two weeks, a second notice will be generated and a copy sent to the next level of management. In addition, failure to resolve investigations may result in the issuance of a work restriction for the individual.
If you agree with the dose estimate, please obtain all signatures and return the completed report to the Dosimetry Distribution Center, Department 7715 within two weeks so that we may update our records.

If either you or the employee disagree with the dose estimate or if you have additional information, please note this information on the investigation report and return it to Radiation Dosimetry Division 7715, within two weeks. Following additional investigation, another report will be sent for your signature.

If you have any questions regarding this Non-Returned Dosimeter Investigation Report, call 4-7725.

VER921204

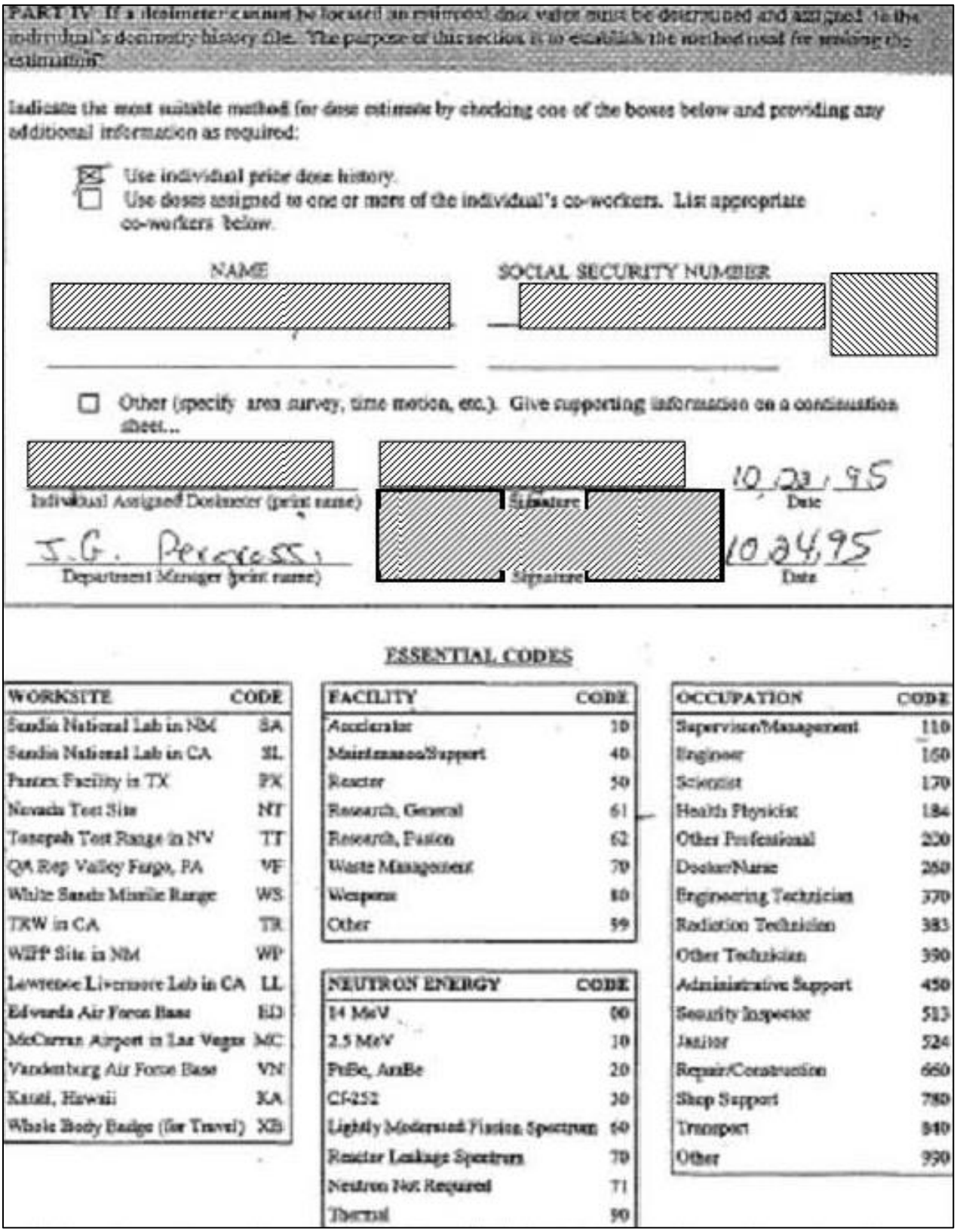
Copy to:
07715 Dosimetry File

AREA HEALTH PHYSICISTS

Area I	Richard Stump	844-5843
Area II & IV	Martin Chen	845-7502
Area III & V	Tom Laiche	845-3271
Livermore	Donn Wright	(510) 294-
NTS	Jim Metcalf	2615

Figure B-5. Example unreturned dosimeter questionnaire follow-up letter.

ATTACHMENT B
DOSIMETRY PROGRAM ADMINISTRATIVE DOCUMENTATION EXAMPLES (continued)



PART IV If a dosimeter cannot be located an estimated dose value must be determined and assigned to the individual's dosimetry history file. The purpose of this section is to establish the method used for making the estimate.

Indicate the most suitable method for dose estimate by checking one of the boxes below and providing any additional information as required:

☒ Use individual prior dose history.
☐ Use doses assigned to one or more of the individual's co-workers. List appropriate co-workers below.

NAME

SOCIAL SECURITY NUMBER

☐ Other (specify area survey, time motion, etc.). Give supporting information on a continuation sheet...

Individual Assigned Dosimeter (print name)

Signature

10/23/95
Date

J.G. Peterson
Department Manager (print name)

Signature

10/24/95
Date

ESSENTIAL CODES

WORKSITE	CODE
Sandia National Lab in NM	SA
Sandia National Lab in CA	SL
Pantex Facility in TX	PX
Nevada Test Site	NT
Tonopah Test Range in NV	TT
QA Rep Valley Fargo, FA	VF
White Sands Missile Range	WS
TRW in CA	TR
WIPP Site in NM	WP
Lawrence Livermore Lab in CA	LL
Edwards Air Force Base	ED
McCarran Airport in Las Vegas	MC
Vandenburg Air Force Base	VN
Kauai, Hawaii	KA
Whole Body Badge (for Travel)	XB

FACILITY	CODE
Accelerator	10
Maintenance/Support	40
Reactor	50
Research, General	61
Research, Fusion	62
Waste Management	70
Weapons	80
Other	99

NEUTRON ENERGY	CODE
14 MeV	00
2.5 MeV	10
PuBe, AmBe	20
Cf-252	30
Lightly Moderated Fission Spectrum	60
Reactor Leakage Spectrum	70
Neutron Not Required	71
Thermal	90

OCCUPATION	CODE
Supervisor/Management	110
Engineer	160
Scientist	170
Health Physicist	184
Other Professional	200
Doctor/Nurse	260
Engineering Technician	370
Radiation Technician	383
Other Technician	390
Administrative Support	450
Security Inspector	513
Janitor	524
Repair/Construction	660
Shop Support	780
Transport	840
Other	990

Figure B-6. Example portion of unreturned dosimeter questionnaire showing various codes used by the Personnel Dosimetry Division.

ATTACHMENT B
DOSIMETRY PROGRAM ADMINISTRATIVE DOCUMENTATION EXAMPLES (continued)

WORK AREA RADIATION DOSIMETRY REQUEST FORM

WORK AREA RADIATION DOSIMETRY

The information supplied on this form and on the accompanying 3.5" diskette will be used to process your work area dosimeters and to produce a written report which will be sent to the individual indicated in Section III below. Dosimeter placement information should be recorded on the reverse side of this document and on the accompanying 3.5" diskette. Return this form along with the dosimeters and the 3.5" diskette to Radiation Protection Measurements Department 7715.

SECTION I - Individual(s) responsible for the placement and/or retrieval of the dosimeters.

PLACEMENT Name: _____ (Last / First / Middle Initial) Org. No.: _____ Phone No.: _____

RETRIEVAL Name: _____ (Last / First / Middle Initial) Org. No.: _____ Phone No.: _____

SECTION II - Dosimeter placement and source information (see continuation on reverse side).

Facility Name: _____ Building/Room No.: _____

_____ Tech Area No. (1-5): _____

USE PERIOD: Date dosimeters placed: ___/___/___ (Mon / Day / Yr) Date dosimeters pulled: ___/___/___ (Mon / Day / Yr)

NUMBER OF: Dosimeters placed in area _____ Dosimeters retrieved at end of monitoring period _____

SOURCE INFORMATION:
High Voltage _____ Operating Current _____
No. of Shots _____ Total Energy Generated _____
Source No. _____ Isotope _____
Other _____

Equipment manufacturer: _____ Model & Serial No.: _____

Neutron Energy Code: _____

AVERAGE NEUTRON ENERGY	CODE
14 (MeV)	01
2.5 (MeV)	10
PuBe, AmBe	20
Cf-252 (Bare)	30
Highly Moderated Fission Spectrum	60
Reactor Leakage Spectrum	70
Neutron Dosimetry Not Required	71
Thermal	99

SECTION III - Reporting requirements.

☐ Deep Dose ☐ Shallow Dose ☐ Neutron Dose ☐ Dose per Shot

SEND REPORT TO: _____ (Last / First / Middle Initial) Org. No.: _____ Phone No.: _____

FOR DOSIMETRY ORGANIZATION USE ONLY

Log. No.: _____ Entered By: _____ (Initials) ___/___/___ (Mon / Day / Yr) Filed By: _____ (Initials) ___/___/___ (Mon / Day / Yr)

Figure B-7. Work Area Radiation Dosimetry Request Form.

ATTACHMENT B
DOSIMETRY PROGRAM ADMINISTRATIVE DOCUMENTATION EXAMPLES (continued)

EXAMPLE REPORT

SANDIA NATIONAL LABORATORIES
HEALTH INSTRUMENTATION DIVISION
SPECIAL DOSIMETRY

Report Date: 02/20/95
Log Number: 95003
Customer: [redacted] MS 1093
Facility: SCO
Field Cycle: 01/05/95 to 01/05/95
Neutron Code: 90
Source Information: BLDG 963 ANNEX: 9 SHOTS
NEUTRON DOSE RESULTS ASSUME DOSIMETERS MOUNTED ON HYDROGENOUS BACKSCATTERER

Number of Shots: 9

Dosimetry Performed By: D. C. Ward, Dept. 7715

The referenced dosimetry was performed using thermoluminescent dosimeters (TLDs). The results are reported in dose equivalent units of rem for Deep (1.0 cm) and Shallow (0.007 cm) tissue depths. The values have had the background dose subtracted. The average dose per shot is also reported.

The statistical or random errors associated with the Deep and Shallow results are less than the larger of +/- 0.005 rem or +/- 10% at the 95% confidence level. The systematic errors are less than +/- 10% and are primarily due to photon energy dependence. The Lower Limit of Detection (LLD) for the deep and shallow dose is 0.010 rem at the 95% confidence level. The dosimetry calibration is performed daily and has traceability to NIST.

The statistical or random errors associated with the neutron results are less than the larger of +/- 0.005 rem or +/- 20% at the 95% confidence level. The systematic errors can be as large as a factor of two (2) and are primarily due to uncertainties in the selection of the neutron fluence and dose conversion factors. The Lower Limit of Detection (LLD) for the neutron dose is a function of the neutron spectrum and ranges from 0.010 to 0.120 rem for low energy to 14 MeV neutrons. The neutron calibration is performed on a phantom and has traceability to NIST.

If there are any questions regarding this information, please call the Dosimetry Office at 844-7197.

Figure B-8. Example work area radiation dosimetry results report.