13

Radiological Dose Assessment

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Introduction

Radiological doses to the public result from both natural and man-made radiation. The doses received by individuals and populations can be determined by measurements and calculations. This chapter describes Lawrence Livermore National Laboratory's radiological dose assessments, which are made to determine the impact of LLNL operations on the public and the environment. It includes a discussion of the analyses performed to demonstrate LLNL's compliance with the radiological *National Emission Standards for Hazardous Air Pollutants* (NESHAPs; Title 40 Code of Federal Regulations [CFR], Part 61, Subpart H).

Background Information

Because this chapter is written for a diverse readership, ranging from scientists and regulators to interested citizens with limited scientific training, a description is given of concepts, methods, tools, and other basic material in the first few sections as well as in Appendix D. Part D-1, "Radiation Basics," covers the different sources and types of radiation and the units used to quantify radiation. It also provides perspective on the wide range of radiation levels that people commonly encounter. Part D-2, "Radiation Control Measures at LLNL," sketches the standard operating procedures used to protect employees, the public, and the environment from uncontrolled releases and unsafe levels of radiation.

A discussion of sources, principal public receptors, and other aspects of modeling and monitoring follows the introductory material in the main text, leading to a presentation of key results on dose impacts from operations conducted in 2002.

Wilhelm Conrad Röntgen discoverer of x-rays in 1885, recipient of first Nobel prize in physics, 1901.

Readers desiring to go directly to these principal new results can turn to the section "Results of 2002 Radiological Dose Assessment."

Releases of Radioactivity to Air

Releases of radioactive material to air (for example, in the form of air effluent dispersed from stacks or wind-driven resuspension of contaminated soil) are by far the major source of public radiological exposures from LLNL operations.

In contrast, releases to groundwater, surface water, and sewerable water are not sources of direct public exposures because these waters are not directly consumed or used by the public. Water releases can cause indirect exposures, which are analyzed as special cases. A case of this type from several years ago concerned the potential dose to the public from inhalation and ingestion of soil that had been contaminated by sewage sludge containing radioactivity (MacQueen et al. 2002). Apart from such unusual occurrences, measurements and modeling of radiological releases to air determine LLNL's dose to the public.

Data supporting LLNL's radiological dose assessment are gathered by three principal means: continuous monitoring of stack effluent at selected facilities at the Livermore site (described in Chapter 4); routine surveillance air monitoring for radioactive particles and gases, both on and off Laboratory property (described in Chapter 5); and radioactive material usage inventories (described in LLNL's NESHAPs annual reports). The inventories cover noncontinuously monitored or unmonitored facilities housing radioactive materials management areas, and the explosive experiments conducted at Site 300.

Despite this emphasis on air monitoring, it should be noted that LLNL's extensive environmental monitoring program encompasses a variety of media and a wide range of potential contaminants; it is not limited to radioactive ones. In addition to ambient and effluent air monitoring and the three categories of water monitoring already mentioned, the Laboratory samples rain water, soil, vegetation, and wine, and measures environmental (gamma) radiation.

Monitoring has been described extensively since 1971 in LLNL's environmental reports (e.g., Gallegos et al. 2002; see also Chapters 4 through 12 in the present report) and in LLNL's *Environmental Monitoring Plan* (Tate et al. 1999) and its companion volume on procedures and guidance documents.

Air Dispersion and Dose Models

Theoretical/computational models are needed to describe the transport and dispersion in air of contaminants and the doses received by exposed persons. Various factors dictate a need for modeling: (1) because the amounts of LLNL-generated radioactive material dispersed into the atmosphere cause doses thousands of times smaller than those caused by natural background radiation (see Appendix D, Part D-1), it is difficult to demonstrate compliance with standards through monitoring (radioisotope-specific measurements are required); (2) all potentially significant exposure pathways need to be taken into account when estimating dose impacts; and (3) the U.S. Department of Energy (DOE) and the U.S. Environmental Protection Agency (EPA) sanction the use of specific computer codes that implement their approved dosimetry and dispersion models for evaluating potential doses to the public from both routine and unplanned releases. Beyond its role in dose assessment for regulatory compliance, the advantages of a well-developed modeling capability include its utility in source design and optimization by estimating effects of hypothetical and/or dangerous sources and in interpreting past events through dose reconstruction.

The computer codes used at LLNL to model air releases and their impacts feature idealized, Gaussian-shaped plumes and can be run on personal computers. The CAP88-PC code incorporates dosimetric and health effects data and equations that are mandated by EPA to be used in compliance assessments (Parks 1992). Furthermore, CAP88-PC accommodates site-specific input data files to characterize meteorological conditions and population distributions for both individual and collective dose evaluations, and the code is relatively easy to use and understand. For these reasons, CAP88-PC has been the "work-horse" modeling tool for LLNL's regulatory compliance assessments since its availability in March 1992, particularly as applied to chronic releases of radioactivity to air occurring in the course of routine operations.

Radiation Protection Standards

The release of radionuclides from operations at LLNL and the resultant radiological impact to the public are regulated by both DOE and EPA.

DOE environmental radiation protection standards, provided under the authority of the Atomic Energy Act of 1954 and the DOE Organization Act of 1977 (both as amended), are defined in DOE Order 5400.5, *Radiation Protection of the Public and the Environment*. The standards for controlling exposures to the public from operations at DOE facilities that are incorporated in this order are based on recommendations by the International Commission on Radiological Protection (ICRP). The radiological impact to the public is assessed in accordance with the applicable portions of DOE Order 5400.1, *General Environmental Protection*.

The primary DOE radiation standards for protection of the public are 1 millisievert per year (1 mSv/y) or 100 millirem per year (100 mrem/y) whole-body effective dose equivalent (EDE) for prolonged exposure of a maximally exposed individual in an uncontrolled area and 5 mSv/y (500 mrem/y) EDE for occasional exposure of this individual. (EDEs and other technical terms are discussed in Appendix D, Part D-1 and defined in the glossary of this report.) These limits pertain to the sum of the EDE from external radiation and the committed 50-year EDE from radioactive materials ingested or inhaled during a particular year that may remain in the body for many years.

Radionuclide emissions to the atmosphere from DOE facilities are further regulated by the EPA, under the authority of Section 112 of the Clean Air Act. Subpart H of NESHAPs, under 40 CFR 61, referenced earlier, sets standards for public exposure to airborne radioactive materials (other than radon) released by DOE facilities; radon is regulated by Subparts Q and T.

The EPA's radiation dose standard, which applies only to air emissions, limits the EDE to members of the public to 100 μSv/y (10 mrem/y). EPA regulations specify not only the allowed levels, but also the approved methods by which airborne emissions and their impacts must be evaluated. With respect to all new or modified projects, NESHAPs compliance obligations define the requirements to install continuous air-effluent monitoring and to obtain EPA approval before the startup of new operations. NESHAPs regulations require that any operation with the potential to produce an annual-averaged off-site dose greater than or equal to 1 μSv/y (0.1 mrem/y), taking full credit for emission-abatement devices such as high-efficiency particulate air (HEPA) filters, must obtain EPA approval prior to the startup of operations. This same calculation, but without taking any credit for emission abatement devices, determines whether or not continuous monitoring of emissions to air from this project is required. These requirements are spelled out in LLNL's online *Environment,*

Safety, and Health (ES&H) Manual, Document 31.1, "Air Quality Compliance," which can be found at the following Internet address: http://www.llnl.gov/es_and_h/hsm/doc_31.01/doc31-01.html

Air Emission Sources and Data

Sources

Nearly a hundred different radioisotopes are used at LLNL for research purposes, including tritium, mixed fission products, transuranic isotopes, biomedical tracers, and others (see **Table 13-1**). Radioisotope handling procedures and work enclosures are determined for each project, depending on the isotopes, the quantities being used, and the types of operations being performed. Work places include glove boxes, exhaust hoods, and laboratory bench tops. Exhaust paths to the atmosphere range from triple HEPA filtered ventilation systems, to roof vents and stacks without abatement devices, to direct dispersal of depleted uranium during explosives testing at Site 300, to a variety of diffuse area sources.

Sources of radioactive material emissions to air at LLNL are divided into two categories for purposes of evaluating regulatory compliance: point sources (including stacks, roof vents, and explosive experiments conducted on firing tables at Site 300) and diffuse area sources (including dedicated waste accumulation areas and other areas of known contamination). Detailed information on releases of radioactivity from LLNL's operations during 2002 is given in *LLNL NESHAPs 2002 Annual Report* (Harrach et al. 2003).

2002 Air Monitoring

This section briefly describes continuous stack-effluent sampling systems at selected LLNL facilities and ambient air monitors in place at numerous

Table 13-1. Radionuclides used at LLNL during 2002

Hydrogen-3	Manganese-54	Technetium-99	Gadolinium-148	Thorium-229	Plutonium-240
Beryllium-7	Iron-55	Rhodium-103	Promethium-151	Thorium-230	Americium-241
Beryllium-10	Cobalt-57	Ruthenium-106	Samarium-151	Protactinium-231	Plutonium-241
Nitrogen-13	Cobalt-58	Cadmium-109	Europium-152	Thorium-232	Curium-242
Carbon-14	Nickel-59	Tin-113	Europium-154	Uranium-232	Plutonium-242
Oxygen-15	Cobalt-60	Iodine-125	Europium-155	Uranium-233	Americium-243
Sodium-22	Nickel-63	Antimony-125	Hafnium-172	Uranium-234	Curium-244
Phosphorus-32	Selenium-75	Iodine-131	Lutetium-174	Uranium-235	Plutonium-244
Phosphorus-33	Strontium-85	Barium-133	Gold-195	Plutonium-236	Curium-246
Sulfur-35	Yttrium-88	Cesium-134	Platinum-195m	Uranium-236	Curium-248
Chlorine-36	Strontium-90	Cesium-137	Bismuth-207	Neptunium-237	Californium-249
Potassium-40	Yttrium-90	Barium-140	Polonium-209	Uranium-237	Californium-250
Argon-41	Niobium-94	Cerium-141	Lead-210	Plutonium-238	Californium-252
Calcium-41	Niobium-95	Cerium-144	Radium-223	Uranium-238	
Scandium-46	Zirconium-95	Neodymium-147	Radium-226	Neptunium-239	
Chromium-51	Molybdenum-99	Promethium-147	Thorium-228	Plutonium-239	

locations on and off LLNL sites. More complete information is provided in Chapters 4 and 5 of this report and in *LLNL NESHAPs 2002 Annual Report* (Harrach et al. 2003).

Continuous Stack Air Effluent Monitoring

Actual measurements of radioactivity in air and effluent flow are the basis for reported emissions from continuously monitored sources. In 2002, there were seven buildings (Buildings 175, 177, 235, 251, 331, 332, and 491) at the Livermore site and one building (Building 801A) at Site 300 that had radionuclide air effluent monitoring systems. The number of samplers, the types of samplers, and the analytes of interest in these buildings are described in Chapter 4.

Air samples for particulate emissions are extracted downstream of HEPA filters and prior to the discharge point to the atmosphere. Particles are collected on membrane filters. The sample filters are removed and analyzed for gross alpha and beta activity. In the pair of 30-meter stacks of the Tritium Facility (Building 331), the analytes being monitored are elemental gaseous tritium (HT), tritiated water vapor (HTO), and total tritium; the sampling utilizes an ionization chamber and molecular sieves (see Chapter 4). Both the Tritium Facility and Plutonium Facility (Building 322) feature monitoring systems with alarm systems.

Air Surveillance Monitoring for Radioactive Particles and Gases

Surveillance air monitoring for tritium and radioactive particles has been in place since the 1970s. LLNL currently maintains seven continuously operating, high volume, air particulate samplers on the Livermore site, nine in the Livermore Valley, eight at Site 300, and one in Tracy. LLNL also maintains twelve continuously operating tritiated water vapor samplers on the Livermore site, six samplers in the Livermore Valley and one at Site 300. The samplers are located to ensure reasonable probability that any significant airborne concentration of particulate or tritiated water vapor effluents resulting from LLNL operations will be detected. Many of the surveillance air monitors are placed near diffuse emission sources, such as those near Buildings 292, 331, 514, and 612, as well as in and around the Southeast Quadrant of the Livermore site. As such, air surveillance information can be used to estimate and/or confirm the emissions from the associated diffuse sources. Also included is an air particulate monitor positioned at the location of the hypothetical maximally-exposed member of the public (defined in the section "Identification of Key Receptors") for the Livermore site. Data from air surveillance monitors provide a valuable test of predictions based on air dispersion modeling and can help characterize unplanned releases of radioactive material.

Radionuclide Usage Inventory Update

A partial accounting of LLNL's radiological emission sources was made in 2002 (as was done in 2001), in accordance with the allowance by EPA that a 100% accounting need be made only every third year. The last 100% accounting was made in 2000.

The partial accounting focused on radiological emission sources in four categories: (1) the group of sources that collectively (in a ranked list) accounted for at least 90% of the dose to the maximally-exposed public individual from both the Livermore site and Site 300 in the 2001 assessment; (2) all "new" sources that commenced emissions in 2002, or sources that showed significantly elevated releases over 2001 levels; (3) all monitored sources; and (4) all sources in the major LLNL waste stream dealt with by Radioactive and Hazardous Waste Management (RHWM) Division in the Environmental Protection Department (EPD).

Radionuclide usage inventory forms, with guidance for completing them, were sent to all assurance managers, facility managers, and project-responsible persons connected with activities meeting these criteria for the partial accounting. The forms were completed by experimenters and certified by facility managers. In particular, radionuclide usage data for all Site 300 explosives experiments and all significant stack and diffuse sources at both sites were included in this update.

Dose Assessment Methods and Concepts

Principal Modeling Approaches

Most estimates of individual and collective radiological doses to the public from LLNL operations were obtained using the EPA-developed computer code CAP88-PC. An LLNL-modified version of this code (designated CAP88-PC-T) that contains an improved tritium model (not yet approved by EPA for use in regulatory compliance evaluations), was also used for purposes of comparison.

The user's guide for CAP88-PC (Parks 1992) provides useful information, including discussions of the basic equations and key input and output files. Additional information about LLNL-site-specific data files and several important caveats on use of the code can be found in the LLNL radiological dose assessment guidance document (Harrach 1998). The four principal pathways of exposure from air releases—internal exposures from inhalation of air, ingestion of foodstuff and drinking water, external exposures through irradiation from contaminated ground, and immersion in contaminated air—are evaluated by CAP88-PC. The doses are expressed as whole-body EDEs in units of mrem/y (1 mrem = 10 μSv). Separate doses for Livermore site and Site 300 emissions are evaluated below.

Other codes, such as EPA's INPUFF code (Peterson and Lavdas 1986) or LLNL's HOTSPOT code (Homann 1994), can be used as needed to address unplanned releases or transient releases from normal operations or accidents. In 2000, the EPA granted regulatory "guideline model" status to two codes—the AERMOD and CALPUFF codes—which are of considerably greater complexity than CAP88-PC, INPUFF, and HOTSPOT. Many other Gaussian-plume-type computer models are available for modeling specific types of releases; see, for example, the annotated lists in *Atmospheric Dispersion Modeling Resources* (Oak Ridge 1995) and *Supplement B to the Guideline on Air Quality Models (Revised)* (U.S. EPA 1993).

A complementary approach to deriving EDEs using the built-in dosimetry model in CAP88-PC or other codes is to explicitly calculate EDEs using mathematical formulas from the U.S. Nuclear Regulatory Commission's Regulatory Guide 1.109 (U.S. NRC 1977), which incorporate dose conversion factors consistent with those in the ICRP's Publication 30 (ICRP 1979 et seq.). This approach, outlined in Appendix C of this report, has been used at LLNL since 1979 and can be used to evaluate annual doses to the public inferred from sampling of local environmental media (air, water, vegetation, and wine).

Identification of Key Receptors

When assessing probable off-site impacts, LLNL pays particular attention to doses received by three hypothetical receptors. First is the dose to the site-wide maximally exposed individual (SW-MEI; defined below) member of the public. Second is the dose to the maximally exposed individual (MEI) member of the public from a given source point. Third is the collective or "population" dose received by people residing within 80 km of either of the two LLNL sites.

The SW-MEI is defined as the hypothetical member of the public at a single, publicly accessible location (where members of the public reside or abide) who receives the greatest LLNL-induced EDE from all sources at a site. For LLNL to comply with the NESHAPs regulations, the LLNL SW-MEI cannot receive an EDE greater than 100 μSv/y (10 mrem/y) from releases of radioactive material to air. Public facilities that could be the location of the SW-MEI include schools, churches, businesses, and residences. This hypothetical person is assumed to remain at this location 24 hours per day, 365 days per year, continuously breathing air having the radionuclide concentration, and consuming a specified fraction of food and drinking water that is affected by the releases of radioactivity from the site. Thus, the SW-MEI dose is not received by any actual individual and is used as a conservative estimate of the highest possible dose to any member of the public. The location of the SW-MEI is sensitive to the frequency distribution of wind speeds and directions and locations of key sources in a given year and can change from one year to the next.

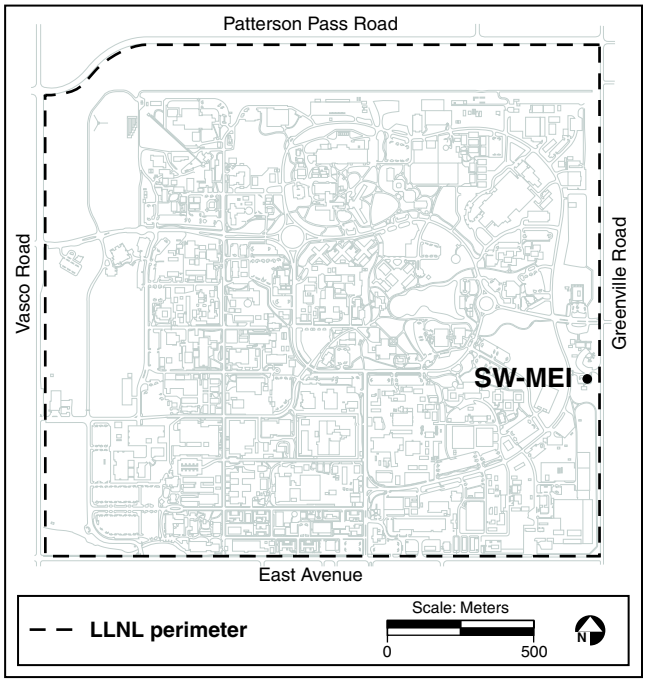

Figure 13-1. Location of the sitewide maximally exposed individual (SW-MEI) at the Livermore site, 2002

At the Livermore site, the SW-MEI in 2002 was, as usual, located at the UNCLE Credit Union, about 10 m outside the controlled eastern perimeter of the site. This location lies 948 m from the Tritium Facility (Building 331), in an east-northeast direction (the typical prevailing wind direction). At Site 300, the SW-MEI occupied a position on the south-central boundary of the site bordering the Carnegie State Vehicular Recreation Area, approximately 3.2 km south-southeast of the firing table at Building 851. These SW-MEI locations are depicted in **Figure 13-1** and **Figure 13-2**.

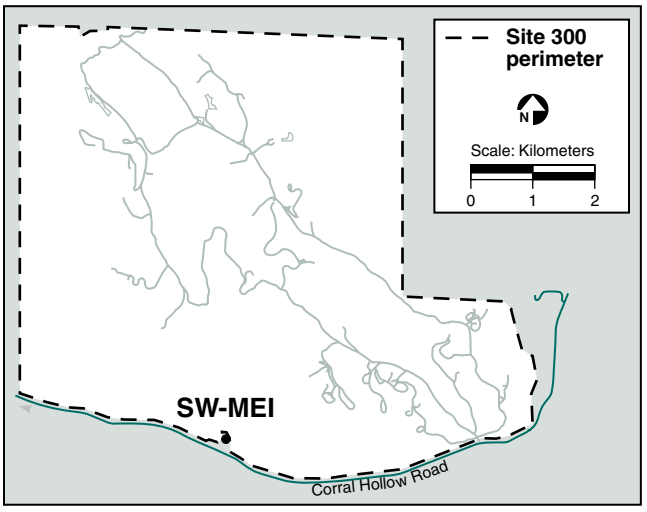

Figure 13-2. Location of the sitewide maximally exposed individual (SW-MEI) at Site 300, 2002

While the SW-MEI location is determined by all sources at a site and coincides with an actual publicly accessible facility, the location of the MEI is any point of unrestricted public access receiving the largest potential dose from a given source and

is generally different for each emission point. Such a point typically occurs at the site perimeter, and is often referred to as the maximum "fence line" dose. However, the off-site maximum dose could occur some distance beyond the perimeter (e.g., when a stack is close to the perimeter).

All new or modified LLNL projects in which releases of radioactivity to the environment may occur are reviewed for joint compliance with NESHAPs and the National Environmental Policy Act (NEPA). Dose to the MEI is used to evaluate whether continuous monitoring of the emissions from a given project is required, and whether it is necessary to petition the EPA for permission to start up the activity.

Summary of Input Parameters to CAP88-PC

General Model Inputs

Basic input parameters for running the CAP88-PC model include the specification of radionuclides, their emission rates in curies per year (1 Ci = 3.7×10^{10} Bq), and data on the nature of the emissions (e.g., stack parameters, including height, diameter, and emission velocity). A complete listing of required input data is given in the *User's Guide for CAP88-PC* (Parks 1992).

Meteorological Data

All model runs used actual 2002 Livermore site and Site 300 meteorological data collected from the meteorological towers for each site. At these towers, wind speed and direction are sampled every few seconds, temperature is sampled every minute, and all are averaged into quarter-hour increments, time tagged, and computer recorded. The data are converted into a CAP88-PC input wind file using EPA guidelines.

Surrogate Radionuclides

CAP88-PC contains a library of 265 radionuclides; however, it does not contain all the radionuclides in use at LLNL. As a consequence, it was necessary in a few cases to derive surrogate radionuclides to estimate EDEs. The *LLNL NESHAPs 2002 Annual Report* (Harrach et al. 2003) shows the surrogate radionuclides used by LLNL in CAP88-PC over the years.

Population Inputs

Population distributions centered on the two LLNL sites were compiled from the LandScan Global Population 1998 Database developed by Dr. Jerome Dobson at Oak Ridge National Laboratory. The population data files (distribution of population with distance and direction) used in the 2002 modeling effort are the same as those described in *LLNL NESHAPs 2000 Annual Report* (Gallegos et al. 2001).

Land Use and Agricultural Inputs

Options for model inputs regarding agricultural characteristics and land use are established by the EPA, and the particular designation selected can strongly influence the ingestion dose received by the population being evaluated. The "user entered" option was again selected for the CAP88-PC modeling effort for 2002. The values entered corresponded to the "local agriculture" option (i.e., everything is home produced), with one exception—all milk consumed was assumed to be imported for individual dose assessment. The assumption that all milk comes from local cows is not supported by the agricultural activities conducted in the area. For population dose assessments, all food is considered to be grown within an 80 km radius about the site; default densities of agricultural products in California are used.

Source Specification

The source term for each emission point in the calculations was determined by one of two methods. For continuously monitored sources, the sampling data (curies released per unit time) for each radionuclide were used directly. For unmonitored facilities, the radionuclide usage inventories, together with time factors and EPA-specified physical state factors, were used to estimate the potential annual emissions to air from a source. The time factors are used to adjust for the fact that the radionuclide may not always be in the same facility all year or may be encapsulated or enclosed for a substantial part of the year. The time factors are chosen to allow a reasonable estimate of the amount of radioactive material that may potentially be released into the atmosphere. The EPA-specified factors for potential release to air of materials in different physical states (solid, liquid, powder, or gas) are those stated in 40 CFR Part 61, Appendix D.

The U.S. EPA has granted approval for LLNL to use alternative physical state factors for elemental uranium, uranium/niobium alloy, and elemental plutonium as described in Table 3 in *LLNL NESHAPs 2002 Annual Report* (Harrach et al. 2003). The physical-state-dependent release fraction and the time factor are used to adjust the total annual usage inventory to yield the potential annual release to air.

In addition, emission control abatement factors (40 CFR 61, Appendix D), when applicable, were applied. Each HEPA filter stage was given a 0.01 abatement factor. Abatement factors are taken into account in an evaluation for start up of operations, but are not included in the evaluation of need to conduct continuous monitoring of emissions.

Special Modeling Challenges

Among the sources at LLNL, explosives tests using depleted uranium at Site 300 and diffuse sources at both sites required special consideration.

Site 300 Explosives Experiments: Some of the assemblies for Site 300 explosives experiments contain depleted uranium and possibly other radioactive materials. (The radioactive material does not contribute to the explosive energy, which is entirely chemical in origin.) The explosives assemblies are placed on an open-air firing table and detonated. Only limited data are available to characterize the initial state of the cloud of explosive decomposition products created by the detonation because properties of the cloud are not routinely measured in the experiments. Empirical scaling laws can be used, however, to define the size and height of the cloud using explosives inventories. The modeling methodology LLNL uses for compliance purposes for modeling these short duration explosive events is discussed in the *LLNL NESHAPs 2002 Annual Report* (Harrach et al. 2003).

Diffuse Sources: Diffuse emissions generally arise from extended-area sources external to buildings. Such sources are difficult to quantify. At present there are no EPA-mandated methods for estimation or measurement of diffuse sources; dose calculations associated with this type of source are left to the discretion of the DOE facility. Dose assessments for Livermore site and Site 300 diffuse sources vary based on radionuclide usage inventory data, environmental surveillance monitoring data, samples of contaminated materials, and other methods. The doses from principal diffuse sources in 2002 are described in the *LLNL NESHAPs 2002 Annual Report* (Harrach et al. 2003).

Modeling Dose from Tritium

Tritium (^{3}H) emissions account for the major dose from operations at the Livermore site. These emissions exist in two major chemical forms: tritium oxide or HTO and HT. The CAP88-PC code's tritium model calculates dose from inhalation, skin absorption, and ingestion of tritium, but only in its HTO form. CAP88-PC's tritium model is based on the specific activity model, which assumes that the tritium-to-hydrogen ratio in body water is the same as in air moisture. Because the specific activity model is linked in CAP88-PC with relatively high dose coefficients for HTO, the model's dose predictions generally err on the high side (see Appendix C).

Doses from inhalation of unit concentration of HT in air are a factor of 15,000 times lower than those from inhalation and absorption through skin of unit concentration of HTO in air (ICRP 1995). Thus, doses from inhaled HT can safely be ignored unless the air concentration is extremely high. A release of HT cannot be ignored, however, because HT that reaches the ground is readily converted to HTO by microorganisms in soil (McFarlane, Rogers, and Bradley 1978) and to a lesser extent in vegetation (Sweet and Murphy 1984).

A third important form of tritium to consider is organically bound tritium (OBT), which is formed by plants during photosynthesis and incorporated by animals when ingested. Animals also metabolize some OBT from ingested or inhaled HTO. The ICRP dose coefficient for OBT is about 2.3 times higher than that of HTO, because the biological half-life of OBT in the body is longer than that of HTO, which is eliminated at the same rate as body water.

A new, simple tritium model developed at LLNL, called NEWTRIT, calculates ingestion dose from both HTO and OBT and accounts for conversion of HT to HTO in the environment after releases of HT (Peterson and Davis 2002). In 2000, LLNL began using the NEWTRIT model incorporated into CAP88-PC (called CAP88-PC-T) in addition to the default CAP88-PC code to estimate doses from significant sources of tritium emissions. A brief discussion of the NEWTRIT model was presented in the *LLNL NESHAPs 2000 Annual Report* (Gallegos et al. 2001).

In late 2002, the EPA had NEWTRIT coded into GENII-NESHAPs, a version of GENII (Napier et al. 1988) that the EPA intends to approve as a regulatory model for compliance with radionuclide NESHAPs (40 CFR 61 Subpart H). GENII-NESHAPs is being peer reviewed.

Results of 2002 Radiological Dose Assessment

This section summarizes the doses to the most exposed public individuals from LLNL operations in 2002, shows the temporal trends by comparison to previous years, presents the potential doses to the populations residing within 80 km of either the Livermore site or Site 300 and places the potential doses from LLNL operations in perspective with doses from other sources.

Total Dose to Site-Wide Maximally Exposed Individuals

The total dose to the SW-MEI from Livermore site operations in 2002 was 0.23 µSv/y (0.023 mrem/y). Of this, the dose calculated for the SW-MEI from diffuse emissions totaled 0.13 µSv (0.013 mrem) or 57% of the total SW-MEI; the dose due to point sources was 0.10 µSv (0.010 mrem) or 43% of the total SW-MEI. The point source dose includes Tritium Facility HT emissions modeled as HTO, as directed by EPA Region IX. Using NEWTRIT to calculate the dose

for tritium emissions reduced the tritium component of the total dose from 0.20 µSv (0.020 mrem) to 0.15 µSv (0.015 mrem).

The total dose to the Site 300 SW-MEI from operations in 2002 was 0.21 µSv (0.021 mrem). Point source emissions from firing table explosives experiments accounted for 0.18 µSv (0.018 mrem), or 85%, of this total, while 0.033 µSv (0.0033 mrem), or about 15%, was contributed by diffuse sources.

Table 13-2 shows the facilities or sources that accounted for more than 90% of the doses to the SW-MEI for the Livermore site and Site 300 in 2002. Although LLNL has nearly 200 sources with potential for releasing radioactive material to air according to NESHAPs prescriptions, most are very minor. Nearly the entire radiological dose to the public from LLNL operations comes from no more than a dozen sources. In April 2003, EPA granted LLNL permission to use surveillance monitoring in place of inventory-based modeling to account for dose contributions from the numerous minor sources (see *LLNL NESHAPs 2002 Annual Report* [Harrach et al. 2003]).

Dominant radionuclides at the two sites were the same as in recent years. Tritium accounted for about 87% of the Livermore site's calculated dose. At Site 300, practically the entire calculated dose was due to the isotopes uranium-238, uranium-235, and uranium-234 in depleted uranium. Regarding pathways of exposure, the relative significance of inhalation and ingestion depends on the assumptions made about the origin of food consumed. The assumption when assessing individual LLNL doses that milk is imported while the remainder of the food is produced locally results in ingestion dose exceeding inhalation dose in the case of tritium, approximately 80% to 20%, respectively. For uranium, these numbers are nearly reversed: 17% by the ingestion pathway versus 83% via inhalation. LLNL doses from air immersion and ground irradiation are negligible for both tritium and uranium.

Table 13-2. List of facilities or sources whose emissions accounted for more than 90% of the SW-MEI doses for the Livermore site and Site 300 in 2002

Facility (source category)	CAP88-PC dose (µSv/y)	CAP88-PC percentage contribution to total dose
Livermore site		
Building 612 Yard (diffuse source)	0.11[a]	48
Building 331 stacks (point source)	0.081[a]	35
Building 514 Evaporator (point source)	0.012	5.2
Building 612, R102 (point source)	0.011	4.8
Building 331 outside (diffuse source)	0.0087[a]	3.8
Site 300		
Building 851 Firing Table (point source)	0.18	85
Soil resuspension (diffuse source)	0.033	15

a When LLNL's NEWTRIT model is used in CAP88-PC in place of CAP88-PC's default tritium model, the doses for Building 612 yard, Building 331stacks, and Building 331 outside become 0.083 µSv, 0.056 µSv, and 0.0065µSv, respectively, and their percentages of the total dose from Livermore site operations each drop by about 2%.

The trends in dose to the SW-MEI from emissions at the Livermore site and Site 300 over the last 13 years are shown in **Table 13-3**. The general pattern, particularly over the last decade, shows year-to-year fluctuations around a low dose level, staying at or below about 1% of the federal standard. The SW-MEI dose estimates are intentionally conservative, predicting potential doses that are generally higher than would actually be experienced by any member of the public.

Table 13-4 shows the Site 300 SW-MEI dose values attributed to firing table experiments for 1990 through 2002; the table also shows the total amounts of depleted uranium and the total quantity of high explosives used each year in the experiments. (Only explosives experiments that included depleted uranium are considered here; most have none.) The 2002 total dose was indicative of decreased firing table activity compared to the previous year but still typical of levels in the past decade.

Doses from Unplanned Releases

There were no unplanned atmospheric releases of radionuclides at the Livermore site or Site 300 in 2002.

Population Doses

Population doses, or collective EDEs, for both LLNL sites were calculated out to a distance of 80 km in all directions from the site centers using CAP88-PC. As noted earlier, CAP88-PC evaluates the four principal exposure pathways: ingestion through food and water consumption, inhalation, air immersion, and irradiation by contaminated ground surface.

Population centers affected by LLNL emissions include the relatively nearby communities of Livermore and Tracy, the more distant metropolitan areas of Oakland, San Francisco, and San Jose, and the San Joaquin Valley communities of Modesto and Stockton. Within the 80 km outer distance specified by DOE, there are 6.9 million residents included for the Livermore site population dose determination, and 6.0 million for Site 300. Population data files (distribution of population with distance and direction) used for the present report were the same as in the previous two years and described in *LLNL NESHAPs 2000 Annual Report* (Gallegos et al. 2001).

The CAP88-PC result for potential population dose attributed to 2002 Livermore-site operations was 0.0050 person-Sv (0.50 person-rem); the corresponding collective EDE from Site 300 operations was 0.025 person-Sv (2.5 person-rem). These values are both within the normal range of variation seen from year to year.

Doses to the Public Placed in Perspective

As a frame of reference to gauge the magnitude of these LLNL doses, **Table 13-5** compares LLNL doses to average doses received in the United States from exposure to natural background radiation and medical tests. Population doses from LLNL operations in 2002 are about 750,000 times smaller than ones from natural background radiation. The estimated maximum potential doses to individual members of the public from operations at the two LLNL sites in 2002 are more than 13,000 times smaller than ones received from background radiation in the natural environment.

Comparison of 2002 Modeling Results with Tritium Air Surveillance Monitoring Data

Every two weeks throughout the year at eighteen locations on the Livermore site and in the Livermore Valley, air tritium concentrations were monitored and reported (Chapter 5). From these

Table 13-3. Doses (μSv) calculated for the sitewide maximally exposed individual (SW-MEI) for the Livermore site and Site 300, 1990 to 2002

Year	Total dose	Point source dose	Diffuse source dose
Livermore site			
2002	0.23[a]	0.10[a]	0.13
2001	0.17[a]	0.057[a]	0.11
2000	0.38[a]	0.17[a]	0.21
1999	1.2[a]	0.94[a]	0.28
1998	0.55[a]	0.31[a]	0.24
1997	0.97	0.78	0.19
1996	0.93	0.48	0.45
1995	0.41	0.19	0.22
1994	0.65	0.42	0.23
1993	0.66	0.40	0.26
1992	0.79	0.69	0.10
1991	2.34	—[b]	—[b]
1990	2.40	—[b]	—[b]
Site 300			
2002	0.21	0.18	0.033
2001	0.54	0.50	0.037
2000	0.19	0.15	0.037
1999	0.35	0.34	0.012
1998	0.24	0.19	0.053
1997	0.20	0.11	0.088
1996	0.33	0.33	0.0045
1995	0.23	0.20	0.03
1994	0.81	0.49	0.32
1993	0.37	0.11	0.26
1992	0.21	0.21	—[c]
1991	0.44	0.44	—[c]
1990	0.57	0.57	—[c]

a The dose includes HT emissions modeled as HTO as directed by EPA Region IX. EPA Region IX acknowledges that such modeling results in an overestimation of the dose. This methodology is used for purposes of compliance.

b Diffuse source doses were not reported separately from the total dose for the Livermore site for 1990 and 1991.

c No diffuse emissions were evaluated and reported at Site 300 before 1993.

Table 13-4. Annual dose to the SW-MEI from explosives experiments on firing tables at Site 300, 1990 to 2002, related to the total quantity of depleted uranium used in the experiments and the total quantity of high explosives driving the detonations

Year	Annual dose to SW-MEI		Total depleted uranium used in experiments (kg)	Total HE [a] used in depleted uranium experiments (kg)
	μSv	mrem		
2002	0.18	0.018	45	77
2001	0.50	0.050	187	104
2000	0.15	0.015	43	34
1999	0.34	0.034	216	168
1998	0.19	0.019	230	192
1997	0.11	0.011	163	122
1996	0.33	0.033	272	112
1995	0.20	0.020	165	199
1994	0.49	0.049	230	134
1993	0.11	0.011	99	74
1992	0.21	0.021	151	360
1991	0.44	0.044	221	330
1990	0.57	0.057	340	170

a HE = high explosives

Table 13-5. Comparison of background (natural and man-made) and LLNL radiation doses, 2002

Location/source	Individual dose[a]		Population dose[b]	
	(μSv)	(mrem)	(person-Sv)	(person-rem)
Livermore site sources				
Atmospheric emissions	0.23	0.023	0.0050	0.50
Site 300 sources				
Atmospheric emissions	0.21	0.021	0.025	2.5
Other sources[c]				
Natural radioactivity[d,e]				
Cosmic radiation	300	30	1,900	190,000
Terrestrial radiation	300	30	1,900	190,000
Internal (food consumption)	400	40	2,500	250,000
Radon	2,000	200	12,500	1,250,000
Medical radiation (diagnostic procedures)[e]	530	53	3,300	330,000
Weapons test fallout [e]	10	1.0	68	6,800
Nuclear fuel cycle	4	0.4	25	2,500

a For LLNL sources, this dose represents that experienced by the SW-MEI member of the public.

b The population dose is the collective (combined) dose for all individuals residing within an 80-km radius of LLNL (approximately 6.9 million people for the Livermore site and 6.0 million for Site 300), calculated with respect to distance and direction from each site.

c From National Council on Radiation Protection and Measurements (NCRP 1987a, b)

d These values vary with location.

e This dose is an average over the U.S. population.

data, an annual mean concentration of tritium in air at each monitoring location was calculated for comparison with air tritium concentrations predicted by CAP88-PC (**Table 13-6**). The model runs for CAP88-PC used source terms of HTO that represent the three principal tritium sources at the site: Building 331 (Tritium Facility) stacks, the Building 612 Yard waste storage area, and an area outside Building 331. Only released HTO is used as a source term because the air tritium monitors only collect HTO. However, HT as well as HTO is released from Building 331, and a small fraction of HT will be converted to HTO in the environment. What HT is converted will be picked up by the air tritium monitors in addition to the HTO that was released as HTO. Thus, the measured concentrations include a small fraction of HTO derived from HT that is not taken into account by CAP88-PC.

The source term for HTO released from the Tritium Facility was determined from stack air effluent monitoring (Chapter 4); the source term for the area outside B331 was determined from facility operator knowledge and ambient air tritium monitoring. In contrast, the Building 612 Yard emission rate was indirectly inferred from a self-consistent back-calculation, in which the HTO release rate from the Building 612 Yard was adjusted to force agreement with the data provided by the nearest air tritium monitor (the B624 monitor). The ratio of modeled-to-measured concentrations for the B624 monitor is therefore 1.0 by design (**Table 13-6**). The other air tritium samplers include the on-site locations B292, B331, and B514; the perimeter locations CAFE, COW, DWTF, MESQ, MET, POOL, SALV, and VIS; and one off-site location, ZON7 (see Chapter 5). ZON7 is notable because it is in the prevailing downwind direction from the sources and is the site of a drinking water supply for the area.

CAP88-PC's predicted air concentrations equaled or exceeded all observed annual mean concentrations except at B292. This under-prediction at sampler B292 is due to its proximity to a pine tree that is evapotranspiring HTO from the ground (see Chapter 11); this source was omitted from the model runs since it was not one of the principal sources of tritium at LLNL. All but one of the other predictions were within a factor of 1.7 of the observed air tritium concentrations. Even for the lone exception, sampler B514, the over-prediction (2.7) falls within the 90% confidence interval for the accuracy of the CAP88-PC dispersion model, which ranges from a factor of 0.3 to 4.4, based on 51 samples (Jack Faucett Associates 1987). A recent test of CAP88-PC's predicted air concentrations compared with annual mean observed air tritium concentrations at 13 perimeter and off-site locations for 1986 through 2001 (Peterson 2003) showed that ninety-six percent of all predictions fall within a factor of three of the observations, and the fraction of predicted air concentrations greater than observed is slightly greater than one-half.

Estimate of Dose to Biota

In recent years, it has been recognized that a past principle of radiological protection—that by protecting man, other living things are also protected—is not adequate. In 2002, the DOE's standards for protection of the natural environment from the effects of ionizing radiation were approved. The guidance document, "DOE Standard: A Graded Approach for Evaluating Radiation Doses to Aquatic and Terrestrial Biota" (DOE 2002), and the RAD-BCG (Biota Concentration Guides) Calculator (Version 2) were made available. DOE sites are requested to calculate dose to biota based upon this guidance. The guidance includes a manual, spreadsheets, and a database of BCGs. Cases where human access to an area of exposure is restricted or exposure pathways favor biota exposure are especially important to consider.

Table 13-6. Comparison of measured and modeled annual mean concentrations of tritiated water vapor (HTO) in air at selected Livermore locations, 2002

Air monitor (name)	Mean measured concentration (Bq/m^3)	Modeled[a] average concentration (Bq/m^3)	Ratio of modeled-to-measured concentrations	Modeled concentration of tritium in air contributed by the indicated source (Bq/m^3)		
				B331 Stacks	B612 Yard	B331 Outside
B624	2.09	2.1	1.0	0.052	2.1	0.0044
B331	0.370	0.53	1.4	0.0019	0.052	0.48
POOL	0.119	0.13	1.1	0.044	0.044	0.041
B514	0.116	0.31	2.7	0.021	0.29	0.0041
B292	0.0648	0.028	0.43	0.0085	0.012	0.0081
VIS	0.0636	0.098	1.5	0.044	0.048	0.0052
CAFE	0.0619	0.083	1.3	0.025	0.044	0.013
DWTF	0.0536	0.057	1.1	0.044	0.0089	0.0037
COW[b]	0.0452	0.050	1.1	0.037	0.0089	0.0043
SALV[b]	0.0344	0.058	1.7	0.015	0.041	0.0023
MESQ[b]	0.0279	0.036	1.3	0.0074	0.013	0.016
ZON7[b]	0.0245	0.025	1.0	0.019	0.0052	0.0012
MET[b]	0.0169	0.018	1.1	0.0056	0.0070	0.0056
CRED[c]		0.13		0.048	0.074	0.0059

a This result takes into account the three most significant tritium sources; it is the annual-average concentration comprising the sum of the three contributions shown in the far right columns.

b At these locations, more than 25% of the samples were below detection limits. The annual mean includes negative concentrations for all except COW. MET has the lowest percentage of detections (17%).

c The CRED location does not have a tritium surveillance air monitor, but it marks the location of the SW-MEI.

The effort required to show compliance is minimized by several features of the guidance: its use of a graded approach; its allowance of use of existing generic and site-specific data (not requiring new monitoring programs tailored to biota); and the fact that current and proposed standards are not very restrictive. Regarding the latter, the limit on absorbed dose is 10 mGy/d (1 rad/d) for aquatic animals and terrestrial plants, and 1 mGy/d (0.1 rad/d) for terrestrial animals. (See Appendix D, Part D-1, "Radiation Basics," and the Glossary for a discussion of radiation units.)

Screening calculations for LLNL impacts were performed in 2002 using the RAD-BCG Calculator. Each radionuclide in each medium (soil, sediment, surface water) is assigned a derived concentration limit in the guidance. For each measured maximum concentration entered in the spreadsheet, a fraction of the derived concentration limit for that radionuclide is automatically calculated, and the fractions are summed for each medium.

For aquatic and riparian animals, the sum of the fractions for water exposure are added to the sum of the fractions for sediment exposure. Similarly, the fractions for water and soil are summed for terrestrial animals. If the sums of the fractions for the aquatic and terrestrial systems are both less than 1 (i.e., the dose to the biota does not exceed the limit), the site has passed the screening analysis, and the biota are assumed to be protected without further analysis.

In the LLNL assessment, the maximum concentration of each radionuclide measured in soils, sediments, and surface waters during 2002, whether measured on the Livermore site, offsite in the Livermore Valley, or at Site 300, was entered into the screening calculation. This approach results in an assessment that is unrealistically conservative, given that the maximum concentrations in the media are spread over a very large area, and no animal could possibly be exposed to them all. It does indicate that no form of biota is put at risk by LLNL operations. Other conservative assumptions provide further reinforcement. For example, only gross alpha and gross beta are measured in water, but, for the biota assessment, it has been assumed that gross alpha is represented by plutonium-239 and gross beta by strontium-90. Furthermore, although biota would most likely live in and near permanent bodies of water (i.e., surface water), measurements of storm water runoff were used for the assessment because the surface water concentrations were below the limit of detection (Table 7-14, Data Supplement). Finally, when measurements were available for both water and sediment, the value (always from sediment) that gave the highest fraction of the BCG was used. (In the software, if a concentration is entered for sediment, a corresponding conservative concentration is calculated by the software, and vice versa.)

Measured radionuclides above the detection limit that might have been contributed by LLNL operations were americium-241, cesium-137, tritium, plutonium-239, thorium-232, uranium-234, uranium-235, and uranium-238. In addition, plutonium-239 and strontium-90 have been used to conservatively represent measurements of gross alpha and gross beta, respectively. The input to the RAD-BCG Calculator is given in **Table 13-7**. For LLNL, the sum of the fractions for the aquatic system was 0.22, and the sum for the terrestrial system was 0.00095. These results are very similar to those in 2001. In 2002, the sum of the fractions of the aquatic system was 5% higher than for 2001; for the terrestrial system, the sum of fractions in 2002 was 59% that of 2001. Both are indicative of doses to aquatic and terrestrial biota from LLNL operations that are well below allowable dose limits.

Dose Summary and Conclusion on Environmental Impact

The annual radiological dose from all emissions at the Livermore site and Site 300 in 2002 was found to be well below the applicable standards for radiation protection of the public, in particular the NESHAPs standard. This standard limits to 100 µSv/y (10 mrem/y) the EDE to any member of the public, arising as a result of releases of radioactive material to air from DOE facilities. Using EPA-mandated computer models and actual LLNL meteorology appropriate to the two sites, the potential doses to the LLNL SW-MEI members of the public from operations in 2002 were:

- Livermore site: 0.23 µSv (0.023 mrem)—43% from point-source emissions, 57% from diffuse-source emissions—calculated by modeling releases of elemental gaseous tritium as tritiated water vapor, for compliance purposes as directed by EPA Region IX.

Table 13-7. Maximum concentrations of radionuclides in water, sediment, and soil on the Livermore site, in the Livermore Valley, and at Site 300 used as input to the RAD-BCG Calculator to assess the effect of LLNL operations on biota

Location	Reference table[a]	Analyte	Maximum concentration
Water (Bq/m^3)			
Site 300: CARW	7.3 DS	Gross alpha[b] (plutonium-239)	370
Livermore site: ASS2	7.1 DS	Gross beta[c] (strontium-90)	850
Site 300; GEOCRK	7.3 DS	Uranium-234	140
Sediment (Bq/kg)			
Livermore site: ESB	10.1 DS	Cesium-137	1.1
Livermore site: WPDC	10.3 MV	Tritium	2.5[d]
Livermore site: WPDC	10.1 DS	Thorium-232[e]	33
Livermore site: WPDC	10.1 DS	Uranium-235[e]	1.5
Livermore site: WPDC	10.1 DS	Uranium-238[e]	24
Soil (Bq/kg)			
LWRP; L-WRP1	10.2 MV	Americium-241	5.4
Site 300; DSW	10.2 DS	Cesium-137	5.0
LWRP; L-WRP1	10.2 MV	Plutonium-239	6.9
Site 300; 851N	10.2 DS	Thorium-232[e]	61
Livermore Valley; ZON7	10.1 DS	Uranium-235[e]	3.3
Livermore Valley; ZON7	10.1 DS	Uranium-238[e]	57

a DS refers to the Data Supplement of this report; MV refers to the main volume.

b It is conservatively assumed that all alpha in the sample is plutonium-239.

c It is conservatively assumed that all beta in the sample is strontium-90.

d Sediment concentrations for tritium are reported by the analytical laboratory both in pCi/L (Table 10-3) and pCi/g soil (shown here).

e Concentrations in the tables referenced are in μg/g dry weight soil or sediment.

- Site 300: 0.21 μSv (0.021 mrem)—85% from explosive experiments, which are classified as point-sources, 15% from diffuse-source emissions.

The major radionuclides accounting for the doses were tritium at the Livermore site and the three isotopes in depleted uranium (uranium-234, uranium-235, and uranium-238) at Site 300. The only significant exposure pathway was release of radioactive material to air, leading to doses by inhalation and ingestion.

The collective EDE or population dose attributable to LLNL operations in 2002 was estimated to be 0.0050 person-Sv (0.50 person-rem) for the Livermore site and 0.025 person-Sv (2.5 person-rem) for Site 300. These doses include potentially exposed populations of 6.9 million people for the

Livermore site and 6.0 million people for Site 300 living within a distance of 80 km from the site centers.

The doses to the SW-MEI members of the public resulting from Livermore site and Site 300 operations in 2002 were below one-quarter of one percent (0.25%) of the federal standard and were more than 13,000 times smaller than the dose from background radiation. The population doses from LLNL operations in 2002 were more than 750,000 times smaller than those caused by natural radioactivity in the environment.

Potential doses to aquatic and terrestrial biota from LLNL operations were assessed and found to be well below DOE allowable dose limits.

Potential radiological doses from LLNL operations were well below regulatory standards and were very small compared with doses normally received by these populations from natural background radiation sources, even though highly conservative assumptions were used in the determinations of LLNL doses. These maximum credible doses to the public indicate that LLNL's use of radionuclides had no significant impact on public health during 2002.