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Radiological Dose Assessment

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Introduction

Radiological doses to the public result from both natural and man-made radiation. The total dose to different populations can be determined by measurements and calculations. This chapter describes LLNL's radiological dose assessments, made to determine the impact of LLNL operations, and contains a discussion of the analyses we performed to demonstrate LLNL's compliance with the radiological National Emission Standards for Hazardous Air Pollutants (NESHAPs; 40 CFR 61 Subpart H).

Background Information

Because this report has a diverse readership, a brief tutorial on radiation is included at the end of the chapter to enable the nonspecialist to understand more easily the radiological dose assessment information. The tutorial, Supplement 12-1: "Radiation Basics," describes the different sources and types of radiation and the units used to quantify it, and provides some perspective on the wide range of radiation levels people commonly encounter. One additional supplement provides ancillary information: Supplement 12-2 describes LLNL's standard operating procedures that protect employees and the public from uncontrolled releases and unsafe levels of radiation. Readers can bypass all discussion of concepts, methods, and tools by proceeding directly to the section on "Radiological Doses from 1997 Operations."

Releases of Radioactivity to Air

Air releases are by far the major source of radiological exposures of the public from LLNL operations. In contrast, releases to water (sewerable, ground, and surface waters) are not sources of direct public exposures, since these waters are not directly consumed or used by the public. Water releases can cause indirect exposures, which are then treated as special cases; for example, inhalation or ingestion of soil contaminated by sewer effluent containing radioactivity. Apart from such unusual occurrences, measurements and modeling of air releases determine LLNL's radiological dose to the public.

Data are gathered by three principal means: routine surveillance air monitoring for radioactive particulates and gases, both on and off Laboratory property (described in Chapter 5); continuous monitoring of stack effluent at selected facilities at the Livermore site (described in Chapter 4); and usage inventories at all non-continuously monitored or unmonitored facilities housing radioactive materials management areas and for radioactive materials used in explosive experiments at Site 300 (described in LLNL's NESHAPs annual reports [e.g., Gallegos et al. 1998]).

Despite this "air emphasis," it should be noted that LLNL's extensive environmental monitoring program embraces all media and a wide range of potential contaminants, not limited to radioactive ones. Monitoring has been covered extensively since 1971 in LLNL's Environmental Reports (e.g., Harrach et al. 1997) (see Chapters 4 through 11 in the present report) and in LLNL's triennially updated *Environmental Monitoring Plan* report (e.g., Tate et al. 1995) and its associated Procedures and Guidance Documents. In addition to air and the three categories of water already mentioned, the Laboratory samples soil, sediment, vegetation, and foodstuff, and measures environmental (gamma) radiation. Concentrations of nonradioactive toxic and hazardous materials as well as radioactive materials in all of these media are reported annually in the *Environmental Report*.

Air Dispersion and Dose Models

Calculational models are needed to describe the transport and dispersion in air of contaminants and the doses experienced by exposed populations. Various factors dictate this need for modeling: (1) the amounts of LLNL-generated radioactive material dispersed into the atmosphere cause doses thousands of times smaller than those caused by natural background radiation (arising from irradiation by cosmic rays, inhalation of radon gas, exposure to radioactive materials in soil and rock, and ingestion of naturally occurring radionuclides present in our food and water), so it is difficult to demonstrate compliance with standards through physical measurements alone; (2) all significant exposure pathways need to be taken into account when estimating dose impacts, entailing the use of a good dosimetry model; 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, and mandate that these codes be used to calculate potential doses to the public from exposures resulting from both routine and unplanned releases. Other advantages of a well-developed modeling capability include its utility in source design and optimization (e.g., estimating effects of hypothetical and/or dangerous sources) and in interpreting past events (e.g., in dose reconstruction).

The computer programs we use to model air releases and their impacts feature gaussian-plume descriptions and can be run on personal computers. The CAP88-PC code (Parks 1992), in particular, incorporates dosimetric and health effects data and equations that are advocated by EPA to be used in compliance assessments. Furthermore, CAP88-PC accommodates site-specific input data files to characterize meteorological conditions and population distributions for a site, and the code is relatively easy to use and understand. For these reasons it has been the "workhorse" calculational tool for LLNL's regulatory compliance assessments since its availability in April 1992, particularly as applied to gradual releases 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 is regulated by both the DOE and the EPA.

DOE environmental radiation protection standards, provided under the authority of the Atomic Energy Act of 1954, as amended, and the DOE Organization Act of 1977, 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 DOE Order 5400.1, *General Environmental Protection*. Current index and links to DOE orders appear on the Department of Energy Directives web site (U.S. Department of Energy 1998).

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, as amended. Subpart H of the National Emission Standards for Hazardous Air Pollutants (NESHAPs) under 40 CFR Part 61, sets standards for public exposure to airborne radioactive materials (other than radon) released by DOE facilities; radon is regulated by Subparts Q and T. NESHAPs implements the dosimetry system recommended by the ICRP in its Publication 26 (International Commission on Radiological Protection 1977).

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) 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 Supplement 12-1 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.

The EPA's radiation dose standard, which only applies to air emissions, limits the whole-body EDE to members of the public caused by activities/operations at a DOE facility to 0.1 mSv/y or 100 μSv/y (10 mrem/y). EPA regulations specify not only the allowed levels, but also specify the approved methods by which airborne emissions and their impacts must be evaluated. With respect to all new and/or modified projects, NESHAPs compliance obligations define the requirements to install continuous air effluent monitoring, and to obtain EPA approval for start-up of 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 HEPA filters, must obtain EPA approval prior to 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 Chapter 12: "Air Quality Compliance," in LLNL's *Environmental Compliance Manual* (LLNL 1996b).

Reporting Requirements

All DOE facilities that conduct significant environmental protection programs are required to prepare an annual *Environmental Report* for the site, covering activities of the previous calendar year involving releases to all media via all pathways. LLNL presents this report to the DOE Operations Office in Oakland, CA (DOE/OAK), from which it is distributed to appropriate program senior officials, the Office of Scientific and Technical Information, EPA, and to other agencies and organizations, as appropriate.

The specific DOE Order requiring production and publication of environmental reports was until recently DOE Order 5400.1, mentioned above. Through DOE's Accelerated Orders Reduction effort in 1995–1997, certain requirements expressed in DOE orders were changed, transferred, or canceled. The requirement for production of site annual environmental reports was transferred to DOE Order 231.1, *Environment, Safety, and Health Reporting*, while DOE Order 5400.1 remains the driver for environmental monitoring plan reports. Requirements for "Radioactive Effluent and On-Site Discharge Data Reports" were deleted entirely.

Because DOE facilities and operations are subject to the regulatory requirements of EPA, in particular 40 CFR Part 61, Subpart H, DOE facilities are required to submit an annual report to the EPA, via DOE, showing compliance with NESHAPs (addressing only releases to air). LLNL NESHAPs annual reports are available for the years 1990 through 1997 (Fisher 1991; Isherwood 1992, Surano et al. 1993b; Harrach et al. 1994; Surano et al. 1995a; Gallegos et al. 1996; Gallegos and Biermann 1997; and Gallegos et al. 1998a). Also available are a mid-1991 NESHAPs report (Hagen et al. 1991b) and seven quarterly NESHAPs reports covering the last quarter of 1991 through the second quarter of 1993 (Lamson 1991, 1992; Biermann and Lamson 1992 a and b; Biermann et al. 1992c, 1993; and Surano et al. 1993a).

Notification of "environmental occurrences" resulting in releases of hazardous materials, including but not limited to radionuclides, from both routine operations and unplanned releases is required under a number of environmental laws, regulations, and DOE orders. Documentation is required under DOE Order 232.1, *Occurrence Reporting and Processing of Operations Information*. Each site annual *Environmental Report* documents that year's environmental occurrences in its "Compliance Summary" chapter (Chapter 2 in this report). Unplanned releases of radioactive material are described annually in both the *Environmental Report* and the NESHAPs report.

Beyond these periodic reporting requirements, DOE Order 5700.6C, *Quality Assurance*, and NESHAPs require that comprehensive and detailed information on LLNL's dose and risk assessment activities be documented as part of a quality assurance program. The LLNL radiological dose assessment guidance document (Harrach 1998) meets this requirement, and provides a level of detail and emphasis that complements the annual reports.

Evaluation of Sources of Radioactive Emissions

The starting point for an assessment of radiological dose is to identify and properly characterize all significant sources of radioactive emissions at a site. Releases to air are emphasized at LLNL, for reasons already noted. Accurate characterization of emission sources is crucial to credible air dispersion and dose modeling, and more generally to correctly gauging the impacts of operations on workers, the public, and the environment. LLNL's sources are determined in three principal ways: (1) by an inventory process, (2) by direct measurement of the emission rate at the source (continuous effluent monitoring), and (3) by monitoring airborne gases and particulates at selected field points in and around the site (continuous surveillance air monitoring).

Inventoried Sources

Radioactive Materials Management Areas (RMMAs) are areas where radioactive materials are used or stored, or where activation products occur. Several RMMAs at the Livermore site have effluent monitoring systems in place in their exhaust pathways, allowing a direct measurement of their emission rates. For unmonitored or non-continuously monitored RMMAs, source terms for potential releases are inferred from radionuclide inventories, in accordance with EPA methods.

Experimenters and facility managers provide inventory data following a protocol designed and administered by LLNL's Environmental Protection Department. A full (100%) inventory is conducted every three years; only the "key" Livermore site facilities, defined as those in a ranked list that collectively accounted for about 90% of the previous year's Livermore site radiological dose to members of the public, are reinventoried annually. LLNL conducted complete radionuclide inventories for operations in 1994 and again in 1997. In addition, all new RMMAs (ones that commenced operations in the year under evaluation) are inventoried, and radionuclide inventories for all Site 300 explosives experiments are newly evaluated each year. A description of LLNL's inventory process, including examples of the inventory form and accompanying instructions, is given in the guidance document for preparation of NESHAPs annual reports (Gallegos et al. 1998b).

For dose-assessment modeling of unmonitored or noncontinuously monitored sources, the effective emission rate is calculated from radiological usage inventories by applying EPA-specified fractions for potential release to air of materials in different physical states (solid, liquid, powder, or gas) for each radioisotope. The inventory quantity (in curies) is multiplied by a state-dependent release fraction to give the potential annual release to air, i.e., the "effective" emission rate, in accordance with 40 CFR Part 61, Appendix D. If the material is an unconfined gas, the release fraction is 1.0; for liquids and powders, 1.0×10^{-3} is used; and for solids, 1.0×10^{-6}. Data on inventories and descriptions of the diffuse sources can be found in the guidance document (Gallegos 1998) and in NESHAPs annual reports for 1993 through 1997 (Harrach et al. 1994; Surano et al. 1995a; Gallegos et al. 1996; Gallegos and Biermann 1997; and Gallegos et al. 1998a).

In summary, for unmonitored and noncontinuously monitored sources, estimated annual emissions for each radionuclide are based on the product of radionuclide quantity from inventory data and EPA potential-release fractions (physical state dependent release-to-air factors). As discussed later, for some purposes these source emissions may be further reduced by emission-control-device abatement factors, if applicable.

Monitored Sources

Stack Effluent Monitoring

Actual measurements of radionuclides in effluent flow are the basis for reported emissions from continuously monitored sources. Currently six buildings at the Livermore site have continuously monitored discharge points: Buildings 175, 251, 331, 332, 490, and 491. These monitoring systems are described in the LLNL *NESHAPs 1997 Annual Report* (Gallegos et al. 1998a), and in Chapter 4: "Air Effluent Monitoring," in this report. Taken together, these buildings feature about 100 continuously operating monitors.

The most significant monitored source in terms of public dose impact is the Tritium Facility, Building 331, at the Livermore site. Each of the two 30-m stacks on this facility have both a continuous-monitoring ion-chamber alarm system and continuous molecular-sieve samplers. The sieve samplers, which can discriminate between tritiated-water vapor (HTO) and molecular tritium (HT), provide the values used for environmental reporting. The alarmed ion chambers provide real-time tritium concentration release levels (HT and HTO). Monitoring of these stacks provides an accurate measure of the total quantity (number of becquerels or curies) of tritium released to the environment, time-resolved over the course of the year, since the stacks have known properties (height, flow rate, and diameter) and the wind field properties (wind speed, direction, and fluctuation characteristics) are continuously monitored, these data are optimal impute to modeling. The quality of data on source emission rates and wind patterns affects the accuracy of air dispersion and dose assessment modeling more than any other input factor.

Effluent monitoring in the other five facilities is designed to detect radioactive particles. In contrast to monitoring unabated tritium gas effluent in the Building 331 stacks, 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. Sample results are generally found to be below the minimum detectable concentration (MDC) of the analysis; for details, consult Chapter 4 in this report, and the *1997 NESHAPs Annual Report* (Gallegos et al. 1998a).

Among the six continuously monitored facilities at the Livermore site, probably only the Plutonium Facility (Building 332) strictly requires monitoring under the EPA's 0.1 mrem / y standard alluded to earlier in the subsection on radiation standards. The other five are continuously monitored for programmatic or other reasons. For example, continuous monitoring is maintained at the Tritium Facility to provide the most direct and accurate measure of its release of tritium to the atmosphere, and continuous monitoring is maintained at the Heavy Elements Facility (Building 251) in lieu of

undertaking a modeling and measurement effort that would be required to demonstrate that monitoring is not needed.

Dose calculations based on effluent monitoring data are expected to be considerably more accurate than those relying on usage-inventory data, physical state release-to-air fractions, and emission-abatement factors.

Surveillance Air Monitoring

To provide wide-area coverage complementing the narrowly focused stack effluent monitoring, surveillance air monitors are placed at selected locations on and in the vicinities of the Livermore site and Site 300 to detect radioactive gases and particulates in ambient air. In addition, dose rates from external penetrating radiation (gamma rays) are measured using thermoluminescent dosimeters (TLDs). Siting of the air monitors and TLDs is done in accordance with the LLNL *Environmental Monitoring Plan* (Tate et al. 1995). Surveillance air monitors are also placed in the vicinity of known diffuse (extended area) emission sources at the Livermore site, specifically those associated with Buildings 292, 331, 514, and 612 and in and around the Livermore site's southeast quadrant, and in on-site locations providing wide coverage of Site 300. These special monitors measure the concentrations of radionuclides present in the air near the sources and allow a direct determination of their environmental impact; see Chapter 5 in this report. In addition to their utility in connection with releases from routine operations, the surveillance air monitors have proven valuable in quantifying the magnitude of accidental releases and their dose impacts.

Determinations of Dose

This section concentrates on the CAP88-PC code, including commenting on its principal features and providing some caveats regarding its use.

Principal Calculational Approaches

LLNL's primary calculational tool for estimating dose and risk from routine operations and most unplanned releases is the computer code CAP88-PC (Parks 1992) as mentioned earlier. Other codes such as EPA's INPUFF code (Peterson and Lavdas 1996) or the HOTSPOT code (Homann 1994) are used as needed to address unplanned releases or short-term releases from experiments or operations.

A complementary approach to deriving EDEs using the built-in dosimetry model in CAP88-PC or other EPA-mandated code is to explicitly calculate doses using mathematical formulas from, e.g., the Nuclear Regulatory Commission's Regulatory Guide 1.109 (U.S. Nuclear Regulatory Commission 1977), which incorporates dose conversion factors consistent with those in the International Commission on Radiation Protection's document ICRP 30 (International Commission on Radiological Protection 1980). This approach, outlined in Appendix B of this report, has been used historically at LLNL (preceding the availability of CAP88-PC), and continues to 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: MEI and SW-MEI

When assessing probable off-site impacts, three potential doses are emphasized: (1) the dose to the "sitewide maximally exposed individual member of the public," abbreviated SW-MEI (defined below and in the glossary), which combines the effects of all emission points at a site, for evaluation under the EPA's 100 μSv / y (10 mrem / y) standard; (2) the dose to the maximally exposed individual member of the public (abbreviated MEI), caused by a given emission point on the site (taking no credit for emission abatement devices), for evaluation of the need to conduct continuous monitoring of that emission point under a 1 μSv / y (0.1 mrem / y) standard [1% of the EPA standard in (1)]; and (3) the collective dose to the populations residing within 80 km of either of the two LLNL sites, adding the products of individual doses received and the number of people receiving them. One additional dose frequently needed is identical to that in (2), except that credit *is* taken for abatement devices that are in place; this dose determines the necessity to petition the EPA for permission to start up an activity (new or modified project) that would cause a dose of 1 μSv / y (0.1 mrem / y) or more to the MEI.

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 (e.g., the Livermore site). Such public facilities include schools, churches, businesses, and residences. This hypothetical person is assumed to reside at this location 24 hours per day, 365 days per year, continuously breathing air having the ground-level radionuclide concentration, and consuming as at least part of his or her diet foodstuffs and drinking water affected by the releases of radioactivity from the site. Thus, this is not a dose actually received by any individual and should be viewed as a health conservative estimate (i.e., overestimate) 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 in a

given year and can change from one year to the next. At the Livermore site, the SW-MEI currently is located at the UNCLE Credit Union, about 10 m outside the controlled eastern perimeter of the site. This location lies 948 m from the principal radionuclide source, the Tritium Facility (Building 331), in an east-northeast direction (the typical prevailing wind direction). At Site 300, the SW-MEI currently is located in an experimental area termed "Bunker 2" operated by PRIMEX Physics International. Bunker 2 lies about 300 m outside the east-central boundary of Site 300. This bunker is 2.38 km east-southeast of the principal firing table at Building 801.

Doses in category (2), with and without allowance for abatement, are a main concern when new projects or changes to existing 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). The possible environmental and worker safety issues raised by each proposed activity or project are examined from several different points of view in a process coordinated by LLNL's Environmental Protection Department, including a review and evaluation of potential emissions of radionuclides and air toxics. Air quality compliance requirements for projects are described in Chapter 12 of LLNL's *Environmental Compliance Manual* (LLNL 1996b).

Modeling Dispersal and Doses with the CAP88-PC Code

CAP88-PC uses a modified gaussian-plume equation to estimate the average dispersion of radionuclides released from up to six co-located sources (stack or area sources). Required input data define the emission sources, the meteorological conditions, the local agricultural characteristics and land use, and the distribution of population surrounding the site. We provide separate data for the Livermore site and Site 300.

Plume rise can be driven either by momentum or buoyancy, or set to a predetermined level. Flat terrain is assumed; variation in radionuclide concentrations due to complex terrain cannot be modeled by CAP88-PC. Assessments are done for a circular grid with a radius of 80 kilometers or less around a facility, allowing up to 20 user-selected radial distances. Concentrations and doses are sector-averaged for each selected radius; i.e., for a given radius from the source, the quoted output value does not pertain just to the plume centerline ground-level value, but is the mean value for that radius across the width of the 22.5-degree sector.

The mathematical models and explicit equations used in CAP88-PC are described in Chapter 8 of Parks' *User's Guide for CAP88-PC* (Parks 1992), hereafter referred to as the *User's Guide,* under the major headings "Environmental Transport," and "Dose and Risk

Estimates." The differences between CAP88-PC and earlier similar codes are discussed in Appendix E of the *User's Guide.*

In the following, various aspects of CAP88-PC are described, tailoring the remarks to LLNL, where appropriate.

Inputs to CAP88-PC

Required data inputs to CAP88-PC are described in Chapter 4 of the *User's Guide.* Here we summarize some of the principal inputs.

Source Term Specification. CAP88-PC allows stack (point) sources or diffuse (extended area) source-types; volume sources are not an option. A default time period assumed in the code is one year, e.g., input source emission rates have units curies per year (Ci/y) and output dose rates are presented in mrem/y.

The emission rate must be specified for each radionuclide. For monitored sources as discussed above, the continuous sampling data on curies released per unit time for each radionuclide can be used; however, for unmonitored sources, the emission rate is calculated from radiological usage inventories by applying EPA-specified fractions for potential release to air of materials in different physical states (solid, liquid, powder, and gas) for each radioisotope. Similar to physical-state release factors, EPA also specifies control-device abatement factors, associated with various emission-control devices, for use in dispersion and dose models: each high-efficiency-particulate-air (HEPA) filter stage is given a 0.01 emission-reduction factor, venturi scrubbers and electrostatic precipitators are each given a 0.05 factor, and each activated-charcoal filter is given a 0.1 factor. Necessary input information on sources besides emission rate includes stack properties (height, diameter, and volumetric flow rate or temperature of gas in the stack) and the area and elevation of diffuse sources.

Certain sources at LLNL, in particular the Site 300 explosive experiments and a variety of diffuse sources at both sites, such as open-air waste storage and waste accumulation areas, and areas where spills or leaks have occurred, require additional analysis to reduce them to a form suitable for entering into a CAP88-PC input data file. Several such non-standard or special sources are discussed below; more detailed descriptions can be found in any of the NESHAPs annual reports for 1993 through 1997 (Harrach et al. 1994; Surano et al. 1995a; Gallegos et al. 1996; Gallegos and Biermann 1997; and Gallegos et al. 1998a) and in the NESHAPs Annual Report guidance document (Gallegos 1998b).

Meteorological Data. The CAP88-PC code accommodates meteorological data, i.e., sensor-determined data files specifying the frequencies of occurrence for different wind

speeds, wind directions, and atmospheric stability classes, and numbers specifying the annually averaged precipitation, temperature, and average height of the atmospheric inversion layer. The atmospheric transport of radioactive materials released to the atmosphere from LLNL is a sensitive function of meteorological conditions. Wind speed, direction, and fluctuation in direction are measured continuously at two meteorological towers, one at the Livermore site and the other at Site 300. Seven Pasquill-Gifford atmospheric stability classes are specified as part of the wind datafile. The meteorological data reside on a DOS computer diskette and are converted into a CAP88-PC input wind file in accordance with EPA guidelines. In Parks' *User's Guide*, Section 4.3.3, Chapter 7, and Appendix B describe the meteorological data and its conversion for use with CAP88-PC. Tables and windroses showing meteorological data for the Livermore site and Site 300 are published annually in the *Environmental Report* (e.g., see Chapter 1 in this report) and the NESHAPs Annual Report (e.g., Gallegos and Biermann 1997).

Population Data. The code also accepts population data files, defining the distribution of population as a function of distance and direction out to a radial distance of 80 km (about 50 miles) from site-center. For specifying populations, each area element in sixteen 22.5-degree compass sectors is bounded above and below by arcs with radii from the set of user-selected distances, and on its sides by radial line segments separating the sectors. In 1993, population distributions centered on the two LLNL sites (treated separately) were compiled from 1990 census data and used as input to the model calculations of collective doses for all persons living within 80 km. (The preparation and installation of population files for use with CAP88-PC is described in Appendix F of the *User's Guide*.) In 1996 and again in 1997, new and improved population files were created for both LLNL sites, based on 1990 census data as before, but made more accurate through the use of commercially available, computer-map-based population data and ArcView geographic information system software; see the *NESHAPs Annual Report for 1996* (Gallegos and Biermann 1997). Key population centers affected by LLNL emissions are the relatively nearby communities of Livermore and Tracy, the more distant large metropolitan areas of Oakland, San Francisco, and San Jose, and the San Joaquin Valley communities of Stockton and Modesto. Within an 80-km radius centered on the Livermore site, 6.3 million residents reside; the corresponding number is 5.4 million for Site 300.

Agricultural Data. The code allows specification of food sources, agricultural characteristics, and land use parameters, as established by the EPA. Arrays of milk cattle, beef cattle, and agricultural crops are automatically generated by the code based on which state (of the United States) is specified, but the user can override these in favor of non-default values for the densities of beef cattle, milk cattle, and the fraction of land cultivated for vegetable crops. Food-source classifications available for selection by the

user are designated "urban," "rural," "local," "regional," "imported," and "entered," where the last type allows the user to specify the fraction of vegetables, milk, and beef that are home-produced, produced in the assessment area (within 80 km), and imported. The particular choice to represent a site can significantly affect the size of the ingestion dose. We conservatively characterize the two LLNL sites as "local" for our collective and individual dose determinations, with one exception. Since there are no dairies located close to either LLNL site, milk is considered to be imported for the purposes of calculating individual doses at locations near the sites, e.g., those to the MEI and SW-MEI. Agricultural data inputs for CAP88-PC are described in Section 4.3.5 and Appendix C of the *User's Guide.*

Radioisotopes. Up to 36 radionuclides can be included in a single run of CAP88-PC, chosen from a total library of 265 radionuclides. Two complex (the U-238 and Th-232 chains) and four simple (the Cs-137, Ba-140, Mo-99, and Pb-210 chains) radioactive decay chains are available, which allow the user to take into account radioactive decays occurring in the plume as it disperses; this feature is only of interest for short-lived radioisotopes. Most of the radionuclides used by LLNL are included among the 265 in the library; for the few that are not, suitable surrogate or health-impact "equivalent" radionuclides must be selected from the CAP88-PC list. In some cases involving mixtures of radionuclides, LLNL experimenters do not have isotopic analyses, but can only identify their radionuclide inventory as gross alpha, gross beta, or gross gamma radiation, or mixed fission products (MFPs). In such cases, for modeling purposes we conservatively represent a given number of curies of gross alpha by the same number of curies of Pu-239; similarly Sr-90 is used to represent both gross beta and MFPs, and ^{137}Cs is used to represent gross gamma radiation.

CAP88-PC Outputs

The CAP88-PC code calculates radionuclide dose rates, concentrations in air, rates of deposition on ground surfaces, concentrations in food, and intake rates to people from ingestion of food produced in the assessment area (using the Nuclear Regulatory Commission Regulatory Guide 1.109 terrestrial food chain models (U.S. Nuclear Regulatory Commission 1977). Summaries of calculated exposures and risks are broken down by organ, pathway, and radionuclide. The output of CAP88-PC is presented in the form of seven "reports," as described in Section 6.2 of the *User's Guide.*

Dose and risk are estimated in CAP88-PC by combining the inhalation and ingestion intake rates, and the air and ground surface concentrations with dose and risk conversion factors in ICRP Publication 26 (International Commission on Radiological Protection 1977). These estimates from CAP88-PC are applicable only to low-level chronic exposures, since the health effects and dosimetric data it uses are based on low-level chronic intakes.

Caveats on Use of CAP88-PC

A number of caveats and other observations on the use of the CAP88-PC code are presented in the LLNL Radiological Dose Assessment Guidance Document (Harrach 1998). A few of the most important of these are given here.

Dose-Rate Conversion Factors in CAP88-PC. Interrogating a CAP-88PC output file showing the dose rate conversion factors used by the code for the 265 radionuclides it includes, one finds that for many radionuclides the factors differ slightly from those in standard references, such as Federal Guidance Report No. 11 (Eckerman et al. 1988). These factors were compiled for the code in 1989 by Eckerman and Nelson (Eckerman and Nelson 1989), using the best information available at that time, which included small differences for such things as standard breathing rates and blood transfer rates relative to those used by Eckerman et al. in producing Federal Guidance Report No. 11. The dose-rate conversion factors in CAP88-PC are discussed in a 1989 EPA report on risk assessment (Eckerman and Nelson 1989).

Assessment Assumptions Regarding Tritium. Several aspects of tritium dose estimates based on CAP88-PC, each important but unrelated to the others, should be noted. (1) Tritium (H-3) emissions account for the major dose from operations at the Livermore site. Tritium exists in two major chemical forms: tritium oxide or vapor (HTO) and elemental molecular tritium (HT), and these forms are distinguished in monitoring the emission of tritium from the stacks of LLNL's Tritium Facility (Building 331). The HTO that enters the body is distributed throughout the entire body and eliminated at the same rate as body water. Only a very small fraction of HT is retained. The effective dose equivalent from exposure to elemental tritium in air is lower by a factor of about 25,000 than an equal exposure from tritium oxide (Eckerman et al. 1988). Thus, emissions of HTO are the major contributor to the tritium dose to the MEI and SW-MEI. Regarding the collective or population dose to people living within 80 km of the Livermore site, HT could contribute a non-negligible part of the tritium dose by means of its conversion to HTO. But conversion of HT to HTO during plume transport and deposition is a complicated (and inefficient) process, so we typically ignore the HT component; a more conservative alternative would be to treat all HT as HTO for the purposes of the population dose calculation. CAP88-PC assumes HTO is meant whenever an inventory of H-3 is input to the code. (2) The dose-rate-conversion factor that CAP88-PC uses for inhalation-plus-dermal-absorption of tritium is out-dated and more conservative than values quoted in recent literature. In 1980, the ICRP in its publication ICRP 30 recommended that skin intake should be 50% of lung intake, revising its earlier recommendation stated in ICRP 2 (1959) that skin intake equals lung intake. The CAP88-PC dose-rate-conversion factor for tritium contains the 1959 recommendation, producing an inhalation-plus-dermal-absorption dose that is too large

by a factor 4/3 relative to the more recent recommendation (see Attachment 3, Gallegos et al. 1996). (3) Finally, CAP88-PC overestimates the ingestion dose from tritium. According to a recent (October 1997) memorandum from Barry Parks, the degree of this overestimate varies depending on input selections. It can be traced to three key assumptions implicit in the software that may not be immediately apparent to the user: (a) the contribution of home-grown food, (b) the distances at which food is produced, and (c) the number of people consuming locally produced food. Documentation on how these overestimates can occur is available on the Internet at the address http://www.er.doe.gov/production/er-80/cap88/tritium.html.

Special Modeling Problems

Unusual releases may require special measurements and calculations to characterize the source. Both the Livermore site and Site 300 provide important examples in this regard.

Diffuse Sources

Often these unusual releases fall into the classification of "diffuse sources." One example is leakage of tritium-contaminated water from an underground tank at Building 292 at the Livermore site, which resulted in the release of tritium to the atmosphere via soil moisture evaporation and root-uptake and transpiration by plants, from one pine tree in particular. A discussion of this source appears in the section on "Livermore Site Diffuse Sources" in the *1993 NESHAPs Annual Report* (Harrach et al. 1994), and subsequent NESHAPs annual reports provide updates. Emissions from certain difficult-to-characterize sources sometimes can be inferred from data obtained by LLNL's routine surveillance air monitoring program, in which the ambient air at selected locations within and outside of Laboratory boundaries is continuously monitored for tritium gas and radioactive particulates. An example in this category is the diffuse tritium source occupying the Building 612 waste storage yard at the Livermore site, which is characterized using data from an air monitor in the yard. Another example is the diffuse source caused by resuspension of depleted uranium in soil at Site 300; an array of seven air monitors allows the annual-average concentration of uranium in air over the site to be determined. A calculational model described in the *1995 NESHAPs Annual Report* (Gallegos et al. 1996) was developed to distinguish between the contribution made to these data by LLNL-operations-contributed uranium, compared to the considerably larger contribution from naturally-occurring uranium. The routine air surveillance monitoring program also has been particularly useful in registering the magnitude of unplanned releases; an example of this type is provided by the accidental release of curium-244 from Building 513 discussed earlier in the subsection on Unplanned Releases.

The reader is referred to LLNL NESHAPs annual reports for descriptions and evaluations of other such sources.

Modeling Dose Impacts from Explosives Experiments at Site 300

Modeling releases of radionuclides into the atmosphere from explosive tests at Site 300 requires special consideration compared to conventional stack or area sources. During experiments, an explosive device containing depleted uranium is placed on an open-air firing table and detonated. A cloud of explosive decomposition products promptly forms over the firing table, typically reaching a height of several hundred meters, and disperses as it is carried downwind. (The depleted uranium does not contribute to the explosive energy, which is entirely of chemical origin.) In the absence of measurements of the properties of the cloud, we assume for modeling purposes that it reaches an initial height and size governed by known empirical scaling laws for detonations (Bowers, personal communication), in which the scaling parameter is the TNT-equivalent explosive mass. The specific equation we use for the maximum elevation reached by the plume is

$$H_{max}(m) = (92.6) \times [\, M_{TNTeq}(kg) \,]^{0.25} + 10,$$

where the explosive TNT-equivalent mass is approximated as

$$M_{TNTeq}(kg) = (1.3) \times M_{TotalHE}(kg),$$

and $M_{TotalHE}$ is the total mass of high explosives of all types used in the detonation. The (assumed) spherical cloud of decomposition products has a diameter given by the similar scaling relation

$$D(m) = (6.4) \times [\, M_{TNTeq}(kg) \,]^{0.333}.$$

The multiplicative factors in the first and third of these expressions have dimensions: in the first equation 92.6 is not a pure number but is 92.6 $m/(kg)^{0.25}$ and in the third the number 6.4 has units $m/(kg)^{0.333}$. Then expressing M_{TNTeq} in kilograms results in a value for H_{max} and D in meters.

Isotopic ratios for depleted uranium are used. The masses of the three uranium isotopes with atomic weights 238, 235, and 234 in depleted uranium occur in the weight-percentages 99.8, 0.2, and 5×10^{-4}, respectively. The inventory for each explosive experiment specifies the mass of depleted uranium used: $M_{DU}(kg)$. Multiplying this quantity by the respective specific activities gives the total number of curies for each isotope in the cloud.

In summary, the data for the isotopes in depleted uranium are:

U-238: Fraction by weight = 0.998
Specific activity = 3.33×10^{-4} Ci / kg
No. curies of U-238 = 3.33×10^{-4} (Ci / kg) $\times$ M_{DU}(kg);

U-235: Fraction by weight = 2.0×10^{-3}
Specific activity = 2.14×10^{-3} Ci / kg
No. curies of U-235 = 4.29×10^{-6} (Ci / kg) $\times$ M_{DU}(kg);

U-234: Fraction by weight = 5.0×10^{-6}
Specific activity = 6.20 Ci / kg
No. curies of U-234 = 3.10×10^{-5} (Ci / kg) $\times$ M_{DU}(kg).

LLNL's modeling of these Site 300 explosive tests to determine the resultant off-site doses is based on the CAP88-PC code. CAP88-PC simulates each explosive experiment or shot as a continuous, year-long, stack-type emission (i.e., the total activity released in a time period of order one minute in the explosion is treated as though it were released gradually over the course of an entire year), with meteorological data appropriate to annual-average conditions at Site 300. As inputs to the code, H_{max} is used as the fixed plume height and D as the stack diameter.

Clearly, this modeling approach does not match the physical events well, and we could easily do better. An alternative INPUFF-code-based modeling methodology that would treat these transient explosive events as short-duration puffs, and which would incorporate some of the effects of the hilly terrain at Site 300, was submitted to EPA for approval in 1992 (Biermann et al. 1993). EPA Region 9 Headquarters decided that from the standpoint of regulatory compliance the use of CAP88-PC to model these explosives experiments was adequate, despite the recognized difficulties.

In the absence of detailed data about the explosive experiments, we make several highly conservative assumptions in our calculations. We assume that (1) 100% of the depleted uranium present in the experiment is completely aerosolized and dispersed as a cloud; (2) the median particle size is the CAP88-PC default value of 1 μm; (3) the lung clearance class for inhaled material is class Y. (Note: Clearance of inhaled material from the lung to the blood or to the gastrointestinal tract depends on the chemical form, e.g., U_3O_8, of the radionuclide, and is classified as D, W, and Y, respectively, for clearance times of order days, weeks, and years.) These assumptions may produce a dose that is too high by a factor of 10 or more. We believe a more realistic release-to-air fraction for the uranium is no greater than 0.2, but we lack sufficient documentation to use a value other than 1.0. Also, the median particle size may be much larger than 1 μm and a sizable

fraction of the aerosolized particles might be more properly characterized by lung clearance class D, which produces a dose by inhalation of depleted uranium that is smaller by a factor of about 16 compared to class Y. Even with these assumptions, the MEI and SW-MEI individual doses, as well as the collective or population dose, that we calculate for the explosive experiments are very small (see, e.g., the Summary and Conclusions section of this chapter).

Radiological Doses from 1997 Operations

About 150 emission points were included in the 1997 modeling runs. These sources were of several types: stacks and other exhaust pathways from buildings (including emissions from all RMMAs in which radiological operations took place); diffuse area sources generally external to buildings; and open-air firing tables at Site 300 where explosives experiments were conducted.

The Livermore site diffuse sources are Hazardous Waste Management's Tank Farm at Building 514 and the waste storage yard and drum sampling areas at its Building 612 Hazardous Waste Management Yard; a tank leakage area at Building 292; the Southeast Quadrant of the Livermore site where resuspension of contaminated soil occurs; and a waste accumulation area at Building 331. Diffuse sources at Site 300 included the total land area on site where evaporation of tritium and resuspension of depleted uranium can occur, and a low-level-waste staging area at Building 804. Fewer explosives experiments containing radioactive materials were conducted at the Site 300 explosives-testing facilities in 1997, compared to the recent past; this was reflected in the smallest estimated potential dose to the Site 300 SW-MEI in the last eight years, when evaluations of public dose impacts from these experiments commenced. This section presents the main results of our calculations for 1997 operations, summarizes them, and exhibits in tables and a figure the trends in these results over recent years. For further details, especially regarding the diffuse sources at the two sites, see the *LLNL NESHAPs 1997 Annual Report* (Gallegos et al. 1998a).

Dose Breakdown by Facility

Table 12-1 lists all LLNL facilities and diffuse sources having the potential to release radioactivity into the environment during 1997. For each facility or building, the table gives the number of stacks or other exhaust avenues discharging radionuclides, lists the dose to the sitewide maximally exposed public individual (SW-MEI) caused by the dominant emission point at each facility, and identifies the types of operations occurring

Table 12-1. Sources of radiation dose from LLNL releases (measured and potential) to air: stacks and other exhaust pathways from buildings containing radioactive materials management areas, and diffuse area sources.[a,b]

Bldg	Facility	Potential emission points	Maximum EDE[c] (μSv/y)	Operations
151	Isotope Sciences; Chemistry & Materials Science Environmental Services Lab	22	1.5×10^{-4}	Application of nuclear and isotope sciences to a wide range of problems; sample analysis of waste streams and environmental media for radionuclide content
166	Laser Isotope Separation	1	0.0[d]	Conversion of uranium to halides and oxides
174	Laser Isotope Separation	1	1.5×10^{-11}	Pulse laser experimentation
175	Laser Isotope Separation	6	0.0[d]	Cleaning and refurbishing of uranium parts
177	Laser Isotope Separation	4	9.4×10^{-4}	Sample preparation, cleaning of parts, processing uranium oxide powders, liquid uranium corrosion studies
194	Physics & Space Technology	2	9.4×10^{-5}	High-energy linear accelerator (LINAC), positron beam generation and experiments
212	Physics & Space Technology	2	6.8×10^{-11}	Physics experiments; residual contamination from previous operation of rotating target neutron source (no longer operating)
222	Chemistry & Materials Science	6	1.3×10^{-6}	Chemical analyses, cleaning equipment, waste samples preparation and analysis, decontamination, spectroscopy, gravimetric
231	Chemistry & Materials Science, Engineering, Safeguards & Security	13	2.8×10^{-6}	Materials research and testing, spin forming, heat treatment, electron-beam welding, grinding/polishing, casting, microscopy, sample preparation, storage
	Mechanical Engineering Vault	1	0.0[d]	Storage of radionuclides
235	Chemistry & Materials Science	3	3.1×10^{-11}	Material structure studies, precision cutting, ion implantation, metallurgical studies
241	Chemistry & Materials Science	3	1.8×10^{-6}	Materials properties research and testing
251	Heavy Elements			Storage of transuranic isotopes prior to disposal
	Seismically Hardened area	4	0.0[d]	
	Unhardened areas	36	3.0×10^{-4}	
253	Hazards Control	7	3.3×10^{-8}	Radiochemical analyses
254	Hazards Control	1	1.1×10^{-10}	Radiochemical analyses of bioassays; analytical services
255	Hazards Control	2	9.8×10^{-5}	Radiation standards and instrument calibration
281	Chemistry & Materials Science	7	1.6×10^{-8}	Sample preparation; wet chemistry laboratory
292	Environmental Programs	3	2.3×10^{-5}	Tritium contamination from prior operations
298	Laser Fusion	3	3.5×10^{-5}	Laser fusion targets research and development

Table 12-1. Sources of radiation dose from LLNL releases (measured and potential) to air: stacks and other exhaust pathways from buildings containing radioactive materials management areas, and diffuse area sources[a,b] (continued).

Bldg	Facility	Potential emission points	Maximum EDE[c] (μSv/y)	Operations
321	Materials Fabrication	5	3.1×10^{-7}	Forming, machining, and manufacturing of uranium parts
322	Mechanical Engineering	1	4.3×10^{-9}	Cleaning and plating of depleted uranium
327	Mechanical Engineering	1	1.6×10^{-7}	Nondestructive ultrasonic material evaluation
331	Tritium	2	7.2×10^{-1}[d]	Tritium research; decontamination and decommissioning operations
332	Plutonium	8	0.0[d]	Plutonium research
361	Biological and Biotechnology Research	13	4.6×10^{-6}	Radiolabeling; biological dosimetry; DNA sequencing, hybridization, and repair; human genome; enzyme assay; radioactive probes
362	Biological and Biotechnology Research	2	9.5×10^{-8}	Dose preparation for animal experiments
363	Biological and Biotechnology Research	3	1.1×10^{-13}	Dispensing samples
364	Biological and Biotechnology Research	2	4.9×10^{-7}	DNA labeling; isolation and purification
365	Biological and Biotechnology Research	3	1.4×10^{-8}	Housing research animals, animal research, equipment decontamination
366	Biological and Biotechnology Research	1	5.9×10^{-8}	DNA labeling
381	Laser Fusion	1	7.0×10^{-9}	Tritium handling for laser target research
391	NOVA Laser	1	7.4×10^{-5}	Housing of high-energy laser; fusion target irradiation
419	Hazardous Waste Management	2	0.0[d]	Decontamination and decommissioning
490	Laser Isotope Separation	1	0.0[d]	U.S. Enrichment Corporation isotope separation operations, including vaporization of uranium for enrichment
491	Laser Isotope Separation	1	0.0[d]	U.S. Enrichment Corporation isotope separation operations
513	Hazardous Waste Management	3	2.2×10^{-3}	Sampling, treatment, and storage of hazardous, mixed, and radioactive waste; drum repacking and sludge stabilization; shredding of solid waste
514	Hazardous Waste Management (see also diffuse sources below)	2	5.1×10^{-3}	Waste consolidation, vacuum filtration of treated waste water
612	Hazardous Waste Management	4	1.4×10^{-2}	Waste consolidation, drum crushing, lab analysis of waste treatment and treatability samples

Table 12-1. Sources of radiation dose from LLNL releases (measured and potential) to air: stacks and other exhaust pathways from buildings containing radioactive materials management areas, and diffuse area sources[a,b] (concluded).

Bldg	Facility	Potential emission points	Maximum EDE[c] (μSv/y)	Operations
625	Hazardous Waste Management	2	8.4×10^{-8}	Repackaging of wastes
810A	Site 300 Firing Table support	1	1.2×10^{-7}	Assembly of explosives
801	Site 300 Firing Table at 801	—[e]	1.1×10^{-1}	Detonation of explosives
	Livermore site diffuse sources[f]	6	See next six entries below.	Storage areas and contaminated ground
292	Underground storage tank	1	6.1×10^{-7}	Tank leakage of tritiated water transpired by plants
331	Tritium Facility (external)	1	1.7×10^{-2}	Outdoor waste accumulation area
514	Hazardous Waste Management Tank Farm	1	9.5×10^{-3}	Liquid waste processing, treatment, and storage
612	Hazardous Waste Management	2	1.6×10^{-1}	Storage of low-level waste; drum sampling and waste accumulation areas (WAAs)
—	Southeast quadrant of Livermore site	1	3.1×10^{-3}	Contaminated ground
	Site 300 diffuse sources[f]	3	See next three entries below.	Contaminated ground and water
—	All Site 300 land area	1	1.1×10^{-3}	Evaporation of tritium from contaminated soil and water
—	All Site 300 land area	1	8.7×10^{-2}	Resuspension of uranium in contaminated soil
804	Open area	1	6.0×10^{-6}	Low-level waste staging area

a *LLNL NESHAPs 1997 Annual Report* (Gallegos et al. 1998a).

b RMMAs in which no operations using radionuclides took place in 1997 or in which all radionuclides were encapsulated or sealed for the entire year are not included in this table. Table entries refer to routine operations, not unplanned releases.

c The maximum effective dose equivalent to the sitewide maximally exposed individual (SW-MEI) member of the public from a single discharge point, among all discharge points modeled for the indicated facility or building. The SW-MEI is defined in the section on Maximally Exposed Individuals and Populations.

d The effluents from the facility are monitored. Zeroes refer to monitored values below the minimum detectable concentration, as discussed in the Monitored Facilities section.

e Open air dispersal in 1997.

f Diffuse sources are described briefly in the section on specifications of source terms, and more fully in the *LLNL 1997 NESHAPs Annual Report* cited in footnote a.

in the building or facility, or the nature of the diffuse source, as the case may be. Corresponding data is included for the Site 300 explosive experiments. Facilities in which no operations using radionuclides took place in 1997 or in which any radionuclides present were encapsulated or sealed for the entire year are excluded from **Table 12-1**.

The principal feature shown in the table is that LLNL has a fairly large number of very small sources. As shown more clearly in subsequent tables, a few sources account for nearly all of the dose to members of the public, and the total dose is quite small compared to federal standards for radiation protection of the public.

Unplanned Releases

The foregoing discussion, as well as all entries in **Table 12-1**, refer to releases occurring during the course of normal operations. Unplanned or accidental releases must be accounted for, as well, in determining the total dose to the public from LLNL activities. As noted in Chapter 2 of this report (both in the subsection on "National Emission Standards for Hazardous Air Pollutants" and in the subsection on "Hazardous Waste Permits"), there was one unplanned release of radioactivity from the Livermore site in 1997, concerning an escape of curium-244 (^{244}Cm) from Building 513 during an operation in which HEPA air filters were being shredded prior to disposal off site as radioactive waste. The Environmental Protection Department's routine surveillance air monitors recorded data during the hours spanning the primary release event and in the days following, at three principal locations, designated SALV (237 m SE of Building 513), CRED (579 m NE), and Building 531 (389 m NNW). In addition, radiation monitors of several types provided data on the indoor air environment, including respirator data, continuous air monitoring data, and high-volume air sampler data. Based on these data, three different theoretical approaches were used to quantify the amount of ^{244}Cm released from Building 513 and determine the probable impact of this release on the public. (1) Because the SW-MEI dose is precisely the dose received at the CRED surveillance air monitor (i.e., this monitor is positioned at the location of our SW-MEI for the Livermore site, the UNCLE Credit Union), the CRED monitor reading, together with the known dose-rate-conversion factor for ^{244}Cm, provided a direct, modeling-independent and meteorological-data-independent estimate of dose to the SW-MEI of 2.1×10^{-3} μSv (2.1×10^{-4} mrem). (2) Air-dispersion modeling was used in concert with the surveillance air monitoring data to make quantitative estimates of both the amount of radioactivity released to the environment in this accident, and the potential dose to the SW-MEI that occurred as a consequence. The CAP88-PC code was run in a "back-calculation" mode, wherein the unknown source strength is "tuned" to

produce output results consistent with the concentrations of Cm^{244} recorded at the three surveillance air monitor locations. The total release of Cm^{244} was selected to be the largest value for which the calculated concentrations agreed (within plus or minus the 2σ measurement uncertainty) with the mean concentrations shown by all of these air monitors. Using parameters corresponding to a "most likely" release scenario, the air-dispersion modeling calculation yielded the result that about 400 nanocuries (nCi, $1\ nCi = 1 \times 10^{-9}$ Ci) were released into the atmosphere, producing a SW-MEI dose that is 57% as large as the aforementioned model-independent estimate based solely on the CRED monitor data. (3) Finally, an analysis of the building ventilation dynamics, utilizing data from radiation monitors located inside Building 513, concluded that the most likely released quantity was 190 Ci. Using this source term in the same air dispersion modeling run as in (2) produces a SW-MEI dose that is 27% of the CRED monitor result. Our final "best estimate" of the SW-MEI dose from this unplanned release of ^{244}Cm from Building 513 is then the CRED monitor result given in (1) above, since it is the most conservative of the three. It should be kept in mind that modeling approaches such as used in (2) and (3) give a *range* of credible estimates for released quantity and dose, caused by making different, but still plausible, assumptions concerning the conditions of the release; we have emphasized the "most likely" values for simplicity and consistency with other doses quoted in this report. This incident and its analyses are described in the *LLNL NESHAPs 1997 Annual Report* (Gallegos et al. 1998a) and in a detailed letter from LLNL to EPA Region IX (Fisher 1998).

There were no unplanned atmospheric releases at Site 300 in 1997.

Doses to Sitewide Maximally Exposed Individuals

The 1997 calculated EDE to the SW-MEI from Livermore site point sources was 0.78 μSv (0.078 mrem). Emissions from the two 30-m stacks at the LLNL Tritium Facility (Building 331) accounted for most of this: 0.75 μSv (0.075 mrem), or 96%. For the Livermore site, the SW-MEI dose caused by diffuse emissions in 1997 was 0.19 μSv (0.019 mrem). Combining point and diffuse sources, the total annual dose was 0.97 μSv (0.097 mrem), divided 80%/20% between point and diffuse source emissions. This is practically the same as last year's total; **Table 12-2** shows the trend over the past eight years.

Table 12-2. Doses (in μSv) calculated for the sitewide maximally exposed individual for the Livermore site and Site 300, 1990 to 1997.

Year	Total dose	Point source dose	Diffuse source dose
Livermore site			
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	2.3	—[a]	—[a]
1990	2.4	—[a]	—[a]
Site 300			
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	—[b]
1991	0.44	0.44	—[b]
1990	0.57	0.57	—[b]

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

[b] No diffuse emissions were reported at Site 300 for years prior to 1993.

The calculated EDE to the SW-MEI at Site 300 in 1997 was 0.20 μSv (0.020 mrem), with 0.11 μSv (0.011 mrem) caused by emissions in the course of explosives experiments at the Building 801 firing table. The remaining 0.088 μSv (0.0088 mrem), or about 45% of the total, was attributed to Site 300 diffuse sources; resuspension of LLNL-contributed uranium in surface soils throughout Site 300 was responsible for nearly all of this dose from diffuse sources.

The 1997 firing tables total is down from values in recent years (see the "point source dose" column for Site 300 in Table **12-2**). **Table 12-3** shows the potential public dose values attributed to firing table experiments for 1990 through 1997, correlated with the total amounts of depleted uranium and the total quantity of high explosives used in the

experiments. (Only experiments that included depleted uranium are considered; most have none.) The data show that variations from year to year in these doses mainly reflect differences in the amount of depleted uranium used in the tests.

Table 12-3. Annual dose to the SW-MEI from explosives experiments on firing tables at Site 300, 1990–1997, related to the total quantity of depleted uranium used in the experiments and the total quantity of high explosives (HE) driving the detonations.

Year	Dose to SW-MEI		Total depleted U used in experiments (kg)	Total HE used in depleted U experiments (kg)
	(μSv)	(mrem)		
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

Table 12-4 lists the facilities that were primarily responsible for the LLNL dose; the contributions from all emission points at each facility have been summed. These facilities accounted for approximately 97% of the total EDE resulting from Livermore site operations and more than 99% of the total EDE from Site 300 operations. The dominant radionuclide(s) are indicated for each facility. Tritium was the overall dominant radionuclide at the Livermore site, accounting for more than 95% of the Livermore site dose. At Site 300, practically the entire dose was due to the isotopes present in depleted uranium having atomic numbers 238, 235, and 234.

The relative significance of inhalation and ingestion is different for tritium and uranium and depends on the assumptions made about the origin of food consumed by a person receiving the dose. For the conditions we assumed when assessing individual doses, namely that milk is imported while the remainder of the food is produced locally, ingestion accounted for 81% of the dose in the case of tritium, versus 19% for inhalation. For uranium, these numbers are nearly reversed: 17% by the ingestion pathway, versus 83% via inhalation. For both uranium and tritium, external doses from air immersion and ground irradiation were negligible.

Table 12-4. Major contributors to LLNL's radiation dose via airborne emissions, 1997.

Facility or operation[a]	Dominant radionuclide(s)	EDE at SW-MEI[b]	
		μSv/y	mrem/y
Livermore site			
B331/Tritium Facility	^{3}H	0.75	0.075
B612 Yard Area[c]	^{3}H	0.16	0.016
B331 Waste Accum. Area[c]	^{3}H	0.017	0.0017
B612	^{238}U, ^{228}Th, ^{239}Pu, ^{137}Cs, ^{234}U, etc.	0.014	0.0014
Sum of all other sources	Various	0.029	0.0029
Total		**0.97[d]**	**0.097[d]**
Site 300			
B801/firing table	^{238}U, ^{234}U, ^{235}U	0.11	0.011
Soil resuspension[c]	^{238}U, ^{234}U, ^{235}U	0.087	0.0087
Total		**0.20[d]**	**0.020[d]**

a The facilities cited here are discussed in the text of this report and in more detail in the NESHAPs annual reports.

b These doses represent the sum of all emission points from a given facility (for example, both stacks on Building 331), in contrast to the dose values in Table 12-1, which represent the dose from the single largest emission point on each facility. The sitewide maximally exposed individual (SW-MEI) member of the public is defined in the section on Maximally Exposed Individuals and Populations.

c Diffuse sources (see text).

d These Livermore site and Site 300 totals represent 0.97% and 0.20%, respectively, of the federal standard.

Ranked List of Radionuclides Used in LLNL Operations

A ranked list showing the most significant 20 of 110 radioisotopes contributing to the radiological dose to the SW-MEI at the Livermore site is presented in **Table 12-5**. In this table, each radionuclide has been assigned a ranking factor that is determined by weighting the effective potential release quantity (in curies) times the inhalation dose rate conversion factor for each particular isotope; ranking is done relative to tritium (tritiated water vapor). Dose rate conversion factors used in the calculations are taken from the CAP88-PC code.

Table 12-5. Leading radioisotopes (with respect to public dose impact) in use at the Livermore site and Site 300 for 1997. The isotopes have been ordered by ranking the potential and measured emissions according to the inhalation dose rate conversion factor for the isotope.

Radionuclides	Ranking factor relative to HTO
H-3 (HTO)	1.0
U-238	2.4×10^{-2}
U-234	6.4×10^{-3}
Am-241	3.7×10^{-3}
Gross alpha	3.5×10^{-3}
Pu-239	2.1×10^{-3}
CM-244	8.9×10^{-4}
Pu-238	8.7×10^{-4}
N-13	6.6×10^{-4}
U-235	5.1×10^{-4}

Radionuclides	Ranking factor relative to HTO
Th-232	4.1×10^{-4}
Th-228	1.1×10^{-4}
O-15	1.1×10^{-4}
Am-244	4.2×10^{-5}
Gd-146	2.7×10^{-5}
P-32	2.5×10^{-5}
Gross beta	2.3×10^{-5}
Am-243	2.0×10^{-5}
Mixed fusion products	1.2×10^{-5}
U-233	7.8×10^{-6}

Trends in Dose to the SW-MEI

The trends in dose to the SW-MEI from emissions at the Livermore site and Site 300 over the last eight years are shown in **Figure 12-1** and **Table 12-2**. No diffuse emissions were reported at Site 300 for years before 1993, so comparison for total dose can only be made with the values for 1993 through 1996. In addition, diffuse source doses were not reported separately from the total dose for the Livermore site for 1990 and 1991. The general trend, particularly over the last half-dozen years, shows year-to-year fluctuations around a quite low dose level, staying at or below about 1% of the federal standard.

The SW-MEI dose estimates we report are intentionally conservative, erring on the side of predicting potential doses that are several times higher than would actually be experienced by any member of the public. Our modeling of Site 300 firing table operations is especially so, as explained in the section on Special Modeling Problems. Our conservative modeling methodology over-predicts the quantity of uranium that is aerosolized and released to air in explosives experiments by at least a factor of five, we believe, and over-estimates the efficiency of long-range dispersal of material in these experiments.

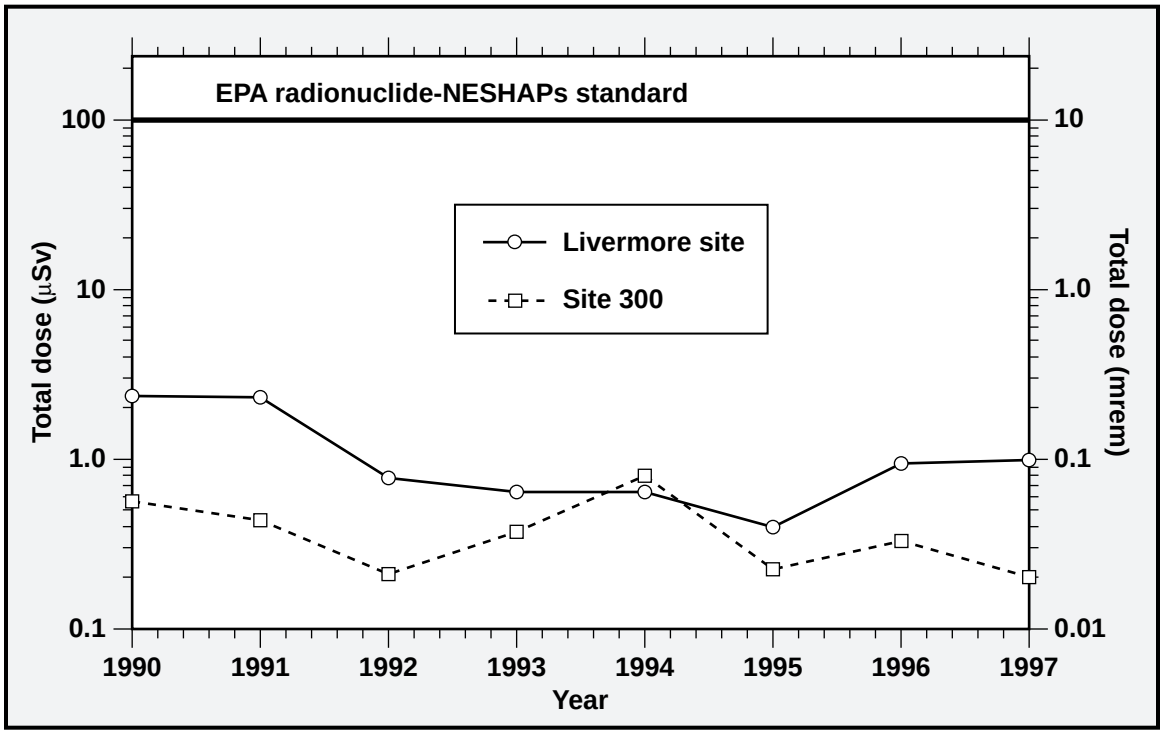

Figure 12-1. Dose to the sitewide maximally exposed individual member of the public, 1990 to 1997.

Collective Doses to Exposed Populations

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.

The collective EDE caused by 1997 Livermore site operations was 1.5 person-rem (0.015 person-Sv), similar to the 1996 result of 1.1 person-rem (0.011 person-Sv). The corresponding collective EDE from Site 300 operations in 1997 was 7.2 person-rem (0.072 person-Sv). This value is lower than the 1996 value of 10 person-rem (0.10 person-Sv). The difference results from use of lesser amounts of depleted uranium in the explosives experiments conducted at Site 300 in 1997 (see **Table 12-2**).

Table 12-6 compares background and medical-treatment-related doses to the maximum potential doses caused by LLNL operations. The population doses caused by LLNL operations are some 400,000 times smaller than ones from natural background radiation, and the individual dose to the maximally exposed public individual is about 3000 times smaller.

Table 12-6. Comparison of background (natural and man-made) and LLNL radiation doses, 1997.

Location/Source	Individual dose[a]		Population dose[b]	
	(μSv)	(mrem)	(person-Sv)	(person-rem)
Livermore site sources				
Atmospheric emissions	0.97	0.097	0.015	1.5
Site 300 sources				
Atmospheric emissions	0.20	0.020	0.072	7.2
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	2000	200	12,500	1,250,000
Medical radiation (diagnostic procedures)[e]	530	53	3,300	330,000
Weapons test fallout[e]	11	1.1	68	6,800
Nuclear fuel cycle	4	0.4	25	2,500

a For LLNL sources, this dose represents that experienced by the sitewide maximally exposed individual 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 6.3 million people for the Livermore site and 5.4 million for Site 300), calculated with respect to distance and direction from each site.

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

d These values vary with location.

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

Summary and Conclusion

The annual radiological dose from all emissions at the Livermore site and Site 300 in 1997 was found to be well below the applicable standards for radiation protection of the public, in particular the NESHAPs standard for DOE facilities, which limits total annual emissions of radionuclides to the ambient air to 100 μSv/y (10 mrem/y). Using EPA-mandated computer models, actual LLNL meteorology, and population distributions appropriate to the two sites, the dose to the LLNL sitewide maximally exposed members of the public from 1997 operations were:

- Livermore site: 0.97 μSv (0.097 mrem) (80% from point-source emissions, 20% from diffuse-source emissions);
- Site 300: 0.20 μSv (0.020 mrem) (55% from explosive experiments, classified as point-sources, 45% from diffuse-source emissions).

The major radionuclides accounting for the doses were tritium at the Livermore site and the three isotopes in depleted uranium (^{238}U, ^{235}U, and ^{234}U) at Site 300).

The collective effective dose equivalent or population dose attributable to LLNL operations in 1997 was estimated to be 0.015 person-Sv (1.5 person-rem) for the Livermore site and 0.072 person-Sv (7.2 person-rem) for Site 300. These doses include exposed populations of 6.3 million people for the Livermore site and 5.2 million for Site 300, living within a distance of 80 km from the site centers, based on 1990 census data.

Table 12-6 compares the individual and collective radiation doses from atmospheric releases at LLNL to other sources of radioactivity to which the U.S. population is exposed. The dose to the maximally exposed member of the public resulting from Livermore site and Site 300 operations is seen to be about 3000 times smaller than the doses from background radiation (see also **Figure 12-2** in Supplement 12-1 below), and the population dose from LLNL operations is about 400,000 times smaller than those caused by natural radioactivity in the environment.

We conclude that the potential radiological doses from LLNL operations were well within regulatory standards and very small compared to 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 indicate that LLNL's use of radionuclides had no significant impact on public health during 1997.

Chapter 12 Supplements

Supplement 12-1: Radiation Basics

Natural and Man-Made Radiation. By far the greatest part of radiation received by the world's population comes from natural sources—primarily cosmic rays that impinge on the earth's atmosphere from space and radionuclides naturally present in our environment, such as radioactive materials in soil and rocks. Among these terrestrial sources are carbon-14, potassium-40, rubidium-87, uranium-238, thorium-232, and radioactive elements, such as radon, that arise from decay of uranium and thorium. The source of human exposure to natural radiation can be external (from substances staying outside the body) or internal (from substances inhaled in air or ingested in food and water). Individual doses vary with location. The level of cosmic radiation increases with altitude, because there is less air overhead to act as a shield, and the earth's poles receive more cosmic radiation than the equatorial regions, because the earth's magnetic field diverts the radiation. The levels of terrestrial radiation differ from place to place around the United States and around the world, mainly owing to variations in soil and rock composition.

Adding to this pervasive natural or background radiation is man-made radiation from radionuclides used in medicine, consumer products, the production of energy, and the production of nuclear weapons. Exposure to man-made sources can be controlled more readily than exposure to most natural sources. However, nuclear explosives tested in the atmosphere in the 1950s and 1960s spread radioactivity across the surface of the globe, and the nuclear reactor accident at Chernobyl in 1986 affected a large area. At present, medical treatment is the largest common source of public exposure to man-made radiation. Individual medical doses vary enormously—someone who has never had an x-ray examination may receive zero medical dose while patients undergoing treatment for cancer may receive many thousands of times the annual average dose they would receive from natural radiation. Another source of public exposure to man-made radiation is consumer products, including luminous-dial watches, smoke detectors, airport x-ray baggage inspection systems, and tobacco products.

Radioactivity. Generally, naturally occurring isotopes are stable, but notable exceptions include carbon-14, potassium-40, thorium-232, uranium-235, and uranium-238, which occur naturally but are radioactive. Nuclear decay divides into three main categories: alpha, beta, and gamma. Alpha decay is the spontaneous emission of an alpha particle (a bound state of two protons and two neutrons—the nucleus of a helium atom) from a nucleus containing a large number of protons (most commonly 82 or more). Beta decay is the spontaneous conversion of a neutron to a proton in the nucleus with the emission of an electron, and gamma decay is the spontaneous emission of high-energy photons (high-frequency electromagnetic radiation) by nuclei.

Radioisotopes decay at quite different rates; the "half-life," or length of time for half of the atoms to decay, spans a wide range from small fractions of a second to millions of years. For example, tritium (the radioactive form of hydrogen) has a 12.3-year half-life, compared to 24,131 years for plutonium-239.

Some radioisotopes decay by forming radioisotopes that in turn decay into other radioisotopes until a stable state is achieved. For example, an atom of uranium-238 can undergo alpha decay, leaving behind a daughter, thorium-234, which is also radioactive. The transformations of the decay chain continue, ending with the formation of lead-206, which is a stable isotope.

Radioactivity can be hazardous because radiation (alpha particles, beta particles, or gamma rays) can be released with great energy. This energy is capable of altering the electronic configuration of atoms and molecules, especially by stripping one or more electrons off the atoms of the irradiated material, thereby disrupting the chemical activity in living cells. If the disruption is severe enough to overwhelm the normal restorative powers of the cell, the cell may die or become permanently damaged. Cells are exposed to many naturally occurring sources of disruption, including naturally toxic chemicals in food, microbes that cause disease, high-energy radiation from outer space (cosmic rays), and heat and light (including the sun's rays, which can cause sunburn and skin cancer). Consequently, cells and living organisms have evolved the capacity to survive limited amounts of damage, including that caused by radioactivity.

Three main factors determine the radiation-induced damage that might be caused to living tissue: the number of radioactive nuclei that are present, the rate at which they give off energy, and the effectiveness of energy transfer to the host medium, i.e., how the radiation interacts with the tissue. Alpha radiation can be halted by a piece of paper and can scarcely penetrate the dead outer layers of skin. Radioisotopes that give off alpha radiation are generally not health hazards unless they get inside the body through an open wound or are ingested or inhaled. In those cases, alpha radiation can be especially damaging because its disruptive energy can be deposited within a small distance, resulting in significant energy deposition in a few cells. Beta radiation from nuclear decay typically penetrates a centimeter or two of living tissue. It therefore deposits energy over many cells, decreasing the damage to any single cell. Gamma radiation is extremely penetrating and can pass through most materials, only being significantly attenuated by thick slabs of dense materials, such as lead.

Measurement of Radioactivity and Dose. The rate at which a nucleus decays is expressed in units of becquerels, abbreviated Bq, where 1 becquerel is one decay per second, or alternatively in curies, Ci, where 1 curie equals 3.7×10^{10} (37 billion) decays per second, or 3.7×10^{10} Bq (approximately equal to the decay rate of 1 gram of pure

radium). Becquerels and curies are not measures of the effect of radiation on living tissue. This depends on the efficiency of energy deposition as the radiation traverses matter.

The amount of energy deposited in living tissue is called the "dose." The amount of radiation energy absorbed per gram of tissue is called the "absorbed dose," and is expressed in units of rads or grays (Gy), where 1 Gy equals 100 rads. Because an absorbed dose produced by alpha radiation is more damaging to living tissue than the same dose produced by beta or gamma radiation, the absorbed dose is multiplied by a quality factor to give the dose equivalent. The quality factor for alpha radiation is 20; for beta and gamma, 1. The dose equivalent is measured in units of rem or sieverts (Sv); 1 Sv equals 100 rem. Also commonly used are the millirem (mrem) and the millisievert (mSv), which are one-thousandth of a rem and sievert, respectively.

Just as one type of radiation can be more damaging than others, some parts of the body are potentially more vulnerable to radiation damage than others, so the different parts of the body are given weightings. For example, a given radiation dose from iodine-131 is more likely to cause cancer in the thyroid than in the lung. The reproductive organs are of particular concern because of the potential risk of genetic damage. Once particular organs are weighted appropriately, the dose equivalent becomes the "effective dose equivalent," also expressed in rem or sievert.

The effective dose equivalent (EDE) describes doses to individuals. When individual effective dose equivalents received by a group of people are summed, the result is called the "collective effective dose equivalent," often referred to as the "population dose," and is expressed in person-sievert or person-rem. Finally, to account for the long-term effects of radionuclides as they continue to decay and affect generations of people, we calculate the dose over many years, summing the effect over time. This is termed the "collective effective dose equivalent commitment." Most of our discussion in this chapter deals with the effective dose equivalent and the collective effective dose equivalent.

Doses from Natural and Man-Made Radioactivity. The average radiation dose from natural sources in the United States, according to the National Council on Radiation Protection and Measurement (NCRP 1987b), is 3.0 mSv / y (300 mrem / y). Approximately 0.3 mSv / y (30 mrem / y) of this exposure comes from high energy radiation from outer space (cosmic rays). Terrestrial sources, mainly radionuclides in rock and soil, also account for approximately 0.3 mSv / y (30 mrem / y) of the average natural dose. Another significant part of the dose comes from radionuclides we ingest through food and drink, resulting in approximately 0.4 m Sv / y (40 mrem / y). Potassium-40 and carbon-14 are common radionuclides in food.

The remaining 2.0 mSv / y (200 mrem / y) or 67% of the average dose from natural sources in the United States comes from radon gas. Radon is one of the major radionuclides produced by uranium decay, and our inhalation dose is dominated by radon's short-lived decay products. **Figure 12-2** shows the distribution of annual radiation doses from natural and other common sources.

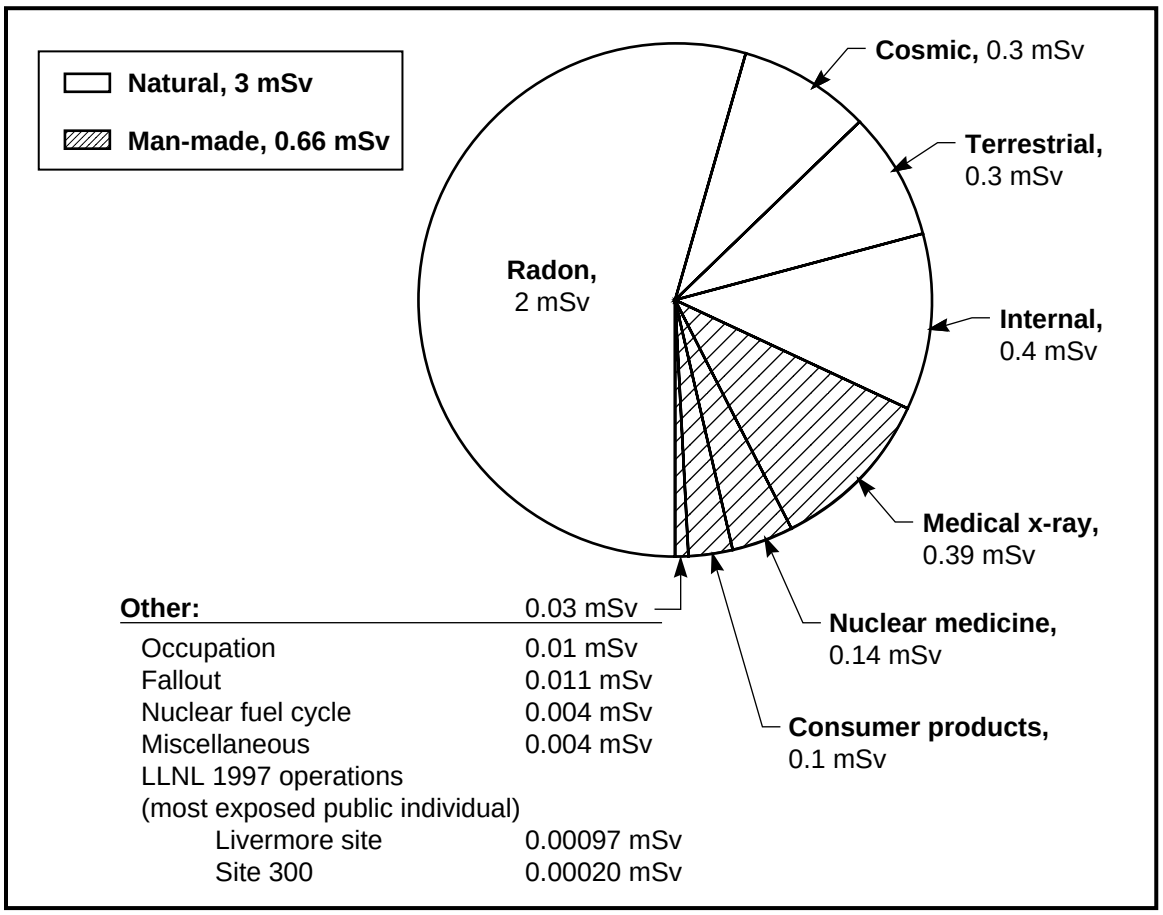

Figure 12-2. Typical annual radiation doses from natural and man-made sources (National Council on Radiation Protection 1987b).

Radon dose varies significantly with geographic location. Levels several times higher than the average occur in some regions of the United States, while at LLNL and its environs doses as low as half the average are typical. Radon gas seeps out of the earth worldwide. Radon in water and natural gas provide additional but less important sources of radon in homes. The U.S. Environmental Protection Agency (EPA) has instituted a major program to educate the public regarding the effects of naturally occurring radon (U.S. Environmental Protection Agency and U.S. Department of Health and Human Services 1986).

The dose received by any particular individual from natural background sources depends on other lifestyle choices or conditions besides place of residency, eating habits, and occupation. For example, the dose from cosmic radiation received in a one-way airplane flight between New York and Los Angeles is about 2.5 mrem; two U.S. coast-to-coast round trip flights give about the same radiation exposure as a standard chest x-ray.

We noted earlier that medical treatment is the largest common source of public exposure to man-made radiation, and most of it is delivered as medical x-rays. These contribute 0.39 mSv (39 mrem) to the average whole-body annual dose in the United States, but individual doses vary enormously. For example, a typical dental x-ray series results in a skin dose (not whole body) of approximately 2.5 mSv (250 mrem). Nuclear medicine contributes 0.14 mSv (14 mrem) to the average dose, and consumer products add 0.1 mSv (10 mrem). For a typical member of the public, radiation from medical procedures and consumer products result in a dose of approximately 0.63 mSv/y (63 mrem/y). The average dose from other man-made sources, including fallout from nuclear testing, is less than 0.03 mSv (3 mrem). As described in this chapter, the contributions from LLNL operations to the dose of even the most affected resident are on the order of 0.1 mrem/y or less, and would not be discernible on the scale shown in **Figure 12-2**; LLNL's contributions are listed under "Other" in the figure.

Supplement 12-2: Radiation Control Measures at LLNL

Radioisotopes used at LLNL include uranium, transuranics, biomedical tracers, tritium, and mixed fission products. Protection of employees and the public from the uncontrolled release of radioactive materials into the environment is a primary consideration for LLNL. This effort takes several forms, as summarized here.

When an operation or facility is designed, a thorough assessment of potential radiation hazards is conducted, and radioisotope-handling procedures and work enclosures are determined for each project, depending on the isotope, the quantity being used, and the type of operations being performed. Radioisotope handling and working environments include glove boxes, exhaust hoods, and laboratory bench tops. The controls might include limiting physical access and using shielding, filters, and remote handling equipment. Exhaust paths to the atmosphere include HEPA (high-efficiency particulate air)-filtered stacks, stacks lacking abatement devices, roof vents, and ordinary room air ventilation channels. Facility Safety Analysis Reports and Facility Safety Procedures are written to document the need for specific measures and to spell out the requirements for maintenance, training, emergency response, and other administrative control measures.

When a facility is occupied for use, an Operational Safety Procedure (OSP) is written that specifies actions to be taken in conducting a research or development project. This procedure is reviewed by environmental analysts, industrial hygienists, and health physicists to assess the safety of the operation, its compliance with current occupational health and environmental standards, and the adequacy of proposed engineering and administrative controls. The OSP also specifies training requirements for personnel. This part of the control program enables LLNL personnel who work with radiation and radioactivity to recognize and prevent the execution of unsafe operations.

Another form of LLNL's radiation control program involves direct monitoring of the workplace environment. This includes sampling of the air and surfaces in facilities where radioactive materials are handled, and includes personal dosimetry and bioassay programs used to monitor potential worker exposure to direct radiation and radioactive isotopes. This monitoring program helps to determine the effectiveness of a facility's radiation control program as well as providing information on worker exposures.

The surveillance and effluent monitoring of radiation in air, water, soils, vegetation, and sewage, as discussed in Chapters 2 and 4 through 11 of this report, play an important role in LLNL's program to control radiation releases. These measurements can signal anomalous releases, should they occur, and directly gauge the degree of success of LLNL's radionuclide discharge control program in limiting exposures of the public.

Development of the Livermore Valley and the San Joaquin Valley has enlarged the populations and decreased the distance between sources of emissions and the residents who might be exposed. People live and work within several hundred meters of LLNL's boundaries. It is therefore increasingly important that our assessments provide the best information possible regarding the radiological impact of LLNL operations.