13. 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).

Because this report is distributed outside the scientific community, we have included a brief preliminary discussion to enable the nontechnical reader to understand more easily the radiological dose assessment information we report. For more information, see *Radiation: Doses, Effects, Risks* (U.N. Environment Programme 1985).

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, 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 naturally occurring 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" 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 13-1** shows the distribution of annual radiation doses from natural and other common sources.

Radon dose varies significantly with geographic location. Levels several times higher than the average occur in some regions of the U.S., 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. Consumption of water high in radon is not the main exposure source; a greater exposure is believed to arise from inhalation of radon in water vapor when showering. The United States 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).

Medical treatment is the largest common source of public exposure to man-made radiation, and most of it is from medical x-rays. These contribute 0.39 mSv (39 mrem) to the average whole-body 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

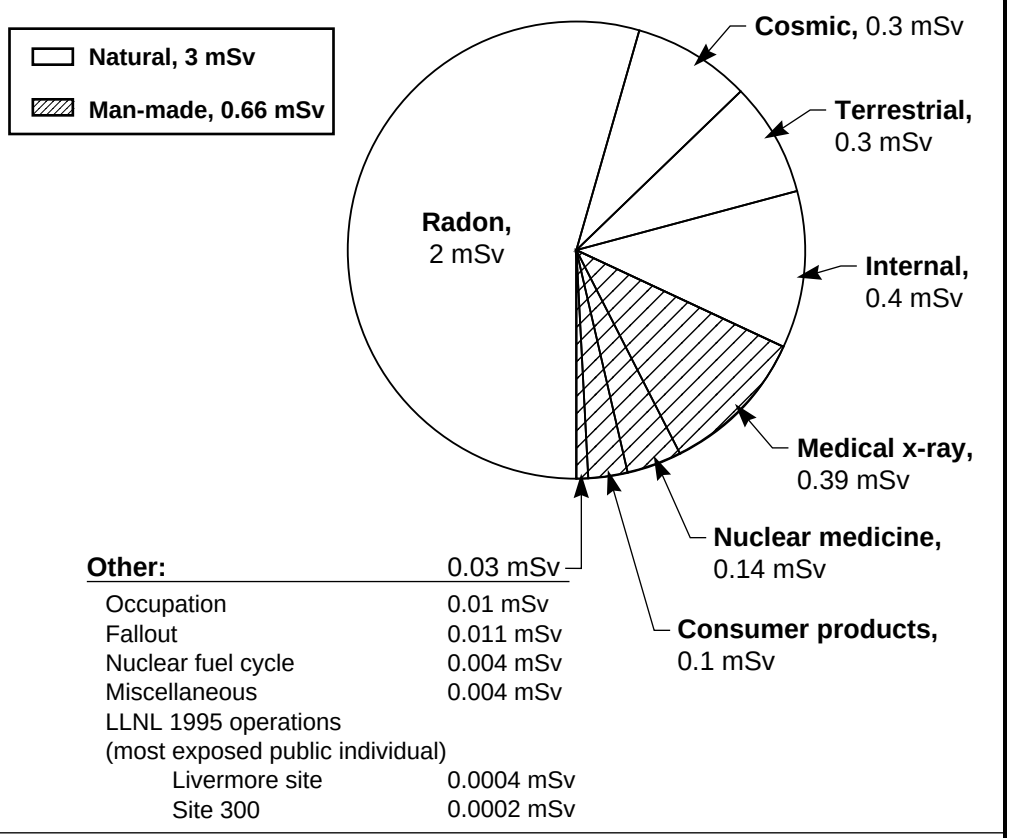

Figure 13-1. Typical annual radiation doses from natural and man-made sources (National Council on Radiation Protection and Measurements 1987b).

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 will be described in the following sections, the contributions from LLNL operations to the dose of even the most affected resident would not be discernible on the scale shown in **Figure 13-1**; these contributions are listed under "Other" in the figure, anticipating our conclusions presented near the end of this chapter.

Radiation Control Measures and Standards

Radioisotopes used at LLNL include uranium, transuranics, biomedical tracers, tritium, and mixed-fission products. This section describes control measures taken to minimize both worker and off-site exposures and presents the federal standards defining allowable radiation exposures to the public from operations at DOE facilities.

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LLNL's Radiation Control Program

Protection of employees and the public from the uncontrolled release of radioactive materials into the environment is a primary consideration for LLNL. This effort consists of several stages. First, 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. Facility Safety Analysis Reports and Facility Safety Procedures are written to document the need for these measures and to specify the requirements for maintenance, training, emergency response, and other administrative control measures.

Another stage of the radiation control program comes into play when a facility is occupied for use. Prior to the conduct of an operation in the facility, an Operational Safety Procedure (OSP) is written that specifies the actions to be taken in conducting a research or development project. This procedure is reviewed by environmental analysts, industrial hygienists, and health physicists. These reviews 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 performing the procedure. This part of the control program enables LLNL personnel who work with radiation and radioactivity to recognize and prevent the execution of unsafe operations.

The next stage of the 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.

Finally, the surveillance and effluent monitoring of radiation in air, water, soils, vegetation, and sewage, as discussed in Chapters 2 and 4 through 12 of this report, are an important indicator of the 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 vital that our assessments provide the best information possible regarding the radiological impact of LLNL operations.

Radiation Protection Standards

DOE environmental radiation protection standards are provided in DOE Order 5400.5, *Radiation Protection of the Public and the Environment* and federal regulation 10 CFR 835, *Occupational Radiation Protection*, which incorporate standards for controlling exposures to the public from operations at DOE facilities. These standards are based on recommendations by the International Commission on Radiological Protection (ICRP 1977, 1980) and the National Council on Radiation Protection and Measurements (NCRP 1987a). The primary DOE radiation standards for protection of the public are 1 mSv/y (100 mrem/y) effective dose equivalent for prolonged exposure, and 5 mSv/y (500 mrem/y) effective dose equivalent for occasional exposure. These limits are based on the dose to the maximally exposed individual in an uncontrolled area, and include all pathways of exposure. The limits apply to the sum of the effective dose equivalent from external radiation and the committed (50-y) effective dose equivalent from radioactive materials that may remain in the body for many years after being ingested or inhaled.

DOE and LLNL also comply with the EPA's standard for radiation protection, promulgated under Section 112 of the Clean Air Act, as amended. This EPA radiation dose standard, which applies to air emissions, is defined in Subpart H of NESHAPs under 40 CFR 61. It limits to 0.1 mSv/y (10 mrem/y) the whole-body effective dose equivalent to members of the public from DOE activities. Before December 15, 1989, the standard was 0.25 mSv/y (25 mrem/y) dose equivalent for whole-body exposures from the air pathway, and 0.75 mSv/y (75 mrem/y) dose equivalent for exposure of any organ from the air pathway.

Because the EPA standard is small and the doses caused by radionuclides released from LLNL are smaller still compared to doses from exposures to natural radioactivity, it would be difficult to prove compliance with the standard by measurements alone. EPA therefore developed computer codes that implement its approved dosimetry model and mandated that these codes be used to calculate potential doses to the public for compliance demonstrations. Calculations reported here used EPA's CAP88-PC code. As described in the following section, it is similar to previous regulatory codes but is improved and expanded. The models used in these codes to evaluate doses and risks contain conservative assumptions that are expected to result in calculated doses larger than ones actually received by members of the public.

Calculations of Radiological Dose

This section presents LLNL's methods for estimating radiological dose. It describes the CAP88-PC air dispersion and dose model, identifies principal doses and maximally exposed individuals, specifies source terms in the model runs, and presents a calculated results summary.

Description of the CAP88-PC Air Dispersion and Dose Model

EPA-mandated computer models were used to carry out our radiological dose assessments, as noted above. Early in 1992, when the CAP88-PC code became available, we began using it exclusively for our standard calculations to take advantage of the significant improvements made in the model. The CAP88-PC code was developed under an Interagency Agreement between DOE and EPA. It provides the capability to compute dose and risk to both exposed individuals and collective populations resulting from radionuclide emissions to air. The differences between CAP88-PC and earlier similar codes such as AIRDOS-PC are discussed in Appendix E of the *User's Guide for CAP88-PC, Version 1.0* (Parks 1992).

CAP88-PC uses a modified Gaussian plume equation to calculate the average dispersion of radionuclides released from up to six sources. Plume rise can be driven by momentum or buoyancy or set to a predetermined level. Flat terrain is assumed; variation in radionuclide concentrations caused by complex terrain cannot be modeled by CAP88-PC. Assessments are done for a circular grid with a radius of 80 km or less around a facility, allowing up to 20 user-selected radial distances. Concentrations and doses are sector-averaged for each area element in the sixteen 22.5° compass sectors; each area element 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. The population in each area element can be set by a user-created population data input file. The mathematical models and explicit equations used in CAP88-PC are described in Chapter 8 of Parks (1992).

CAP88-PC accepts site-specific meteorological, as well as population, data files. Input data for the LLNL modeling are collected from on-site meteorological towers at both the Livermore site and Site 300. Wind speed and direction are sampled every few seconds, temperature every minute, and all are averaged into quarter-hour increments, time-tagged, and computer-recorded for conversion into a CAP88-PC wind file. Numbers specifying the annual average precipitation, temperature, and average height of the atmospheric inversion layer are also put into the model. The code automatically computes results for each of seven Pasquill-Gifford atmospheric stability categories.

CAP88-PC computes radionuclide 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. Calculated doses then include the four principal exposure pathways: internal exposures from inhalation of air and ingestion of foodstuffs and drinking water, and external exposures through irradiation from contaminated ground and immersion in contaminated air. Dose and risk are tabulated as a function of radionuclide, pathway, spatial location, and body organ. Up to 36 radionuclides can be included in a single run, chosen from a total library of 265 radionuclides. The frequency distribution of risk is tabulated, showing the number of people at various levels of risk on a logarithmic scale from 1 in 10 to 1 in 10 million. Dose and risk estimates from

CAP88-PC are applicable only to low-level chronic exposures because the health effects and dosimetric data it uses are based on low-level chronic intakes. The code is not intended for modeling either short-term or high-level radionuclide intakes. The doses are expressed as whole-body effective dose equivalents (EDEs) in units of mrem / y (1 mrem = 10 μSv = 0.01 mSv).

Because CAP88-PC does not contain all the radionuclides present at LLNL, surrogate radionuclides were used in some cases to estimate EDEs. In selecting the surrogates, we used the most restrictive lung class (whether clearance from the lungs takes place in days, weeks, or years). When possible, we used a surrogate radionuclide with similar lung class chemistry and similar values for "annual limits of intake via inhalation and derived air concentration," as specified in the EPA guidance, *Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion* (Eckerman et al. 1988). CAP88-PC contains a library of considerably more radionuclides than earlier regulatory codes, such as AIRDOS-PC. By rerunning calculations with CAP88-PC previously modeled with AIRDOS-PC, we have found that the use of surrogates in the calculations typically results in conservative estimates of EDEs.

Maximally Exposed Individuals and Populations

We report separate determinations of doses for the Livermore site and Site 300. Three potential doses are emphasized: (1) The dose to the sitewide maximally exposed individual member of the public (denoted as SW-MEI and defined below), which combines the effects of all emission points; (2) the maximum dose to any member of the public, in any direction (generally occurring at the site boundary and commonly referred to as the maximum "fence line" dose) due to each emission point on the site; and (3) the collective dose to the populations residing within 80 km of the Livermore site and Site 300 (treated separately), adding the products of individual doses received and the number of people receiving them. Dose to the SW-MEI (the first type above) is used to evaluate LLNL's compliance with the EPA standard limiting the total radionuclide emissions to air from DOE facilities to 100 μSv / y (10 mrem / y) (NESHAPs, 40 CFR Part 61.92, Subpart H). In this evaluation, credit is taken for any emission abatement devices, such as filters that are in place. The second type or fence line dose is calculated without taking credit for any existing emission abatement devices; it is used to evaluate the need for continuous monitoring of individual emission points under the EPA's 1-μSv / y (0.1-mrem / y) standard on potential unabated emissions (40 CFR Part 61.93).

The SW-MEI is defined as the hypothetical member of the public (individual receptor at a residence, place of business, school, church, or similar public facility) who could receive the greatest LLNL-induced EDE from all sources at a single site. At the Livermore site, the SW-MEI is located at the UNCLE Credit

Union, about 10 m outside the controlled eastern perimeter of the site. This location lies 0.95 km from LLNL's principal source of radionuclide emissions to air, the Tritium Facility (Building 331), in an east-northeast direction. At Site 300, the SW-MEI is located in an experimental area termed "Bunker 2" operated by Physics International. Bunker 2 lies about 300 m outside the east-central boundary of Site 300. This bunker is 2.4 km east-southeast of the principal source of radionuclide emissions to air at Site 300, the firing table at Building 801.

It is possible for the location of the SW-MEI to change from year to year, e.g., with changing wind patterns, changing population distributions near site boundaries, or changing emission levels of sources. An illustration of the effect of different wind patterns on dose is given in the *LLNL NESHAPs 1993 Annual Report* (Harrach et al. 1994). Four prime candidates for the SW-MEI were evaluated for the Livermore site in confirming the UNCLE Credit Union location for 1995, as described in the *LLNL NESHAPs 1995 Annual Report* (Gallegos et al. 1996).

Specification of Source Terms in the Model Runs; Point and Diffuse Sources

Emission sources of radionuclides (stacks on buildings, drums in waste storage areas, etc.) are evaluated in two ways. For unmonitored and noncontinuously monitored sources, the releases are estimated from radionuclide inventory data using EPA methods; for continuously monitored facilities, actual emission measurements are used. In this section, we discuss the determination of source terms for these monitored and inventoried facilities, as well as for areas (generally exterior to buildings) at the Livermore site and Site 300 where diffuse emissions occur. Source terms at Site 300 locations where high explosives experiments are carried out are also discussed. New dose-assessment modeling runs, using these source terms and 1995 on-site meteorological data (wind, precipitation, and temperature), were conducted this past year for each key facility and for each new emission point.

Because surface and ground waters impacted by LLNL operations and its sewer effluents are not consumed, they do not represent an ingestion or inhalation pathway for radiation exposure. Therefore, our assessment of radiological dose to the public is based solely on material that enters the environment via air releases.

Table 13-1 lists all LLNL sources having the potential to release radionuclides to air (with some exceptions noted below). The table gives the number of potential radionuclide discharge points associated with each building, lists the largest dose to a public individual due to any one of the emission points at each building, and identifies the types of operations occurring in each building. Facilities in which no operations using radionuclides took place in 1995 or in which any radionuclides present were encapsulated or sealed for the entire year are excluded from **Table 13-1**.

Table 13-1. Sources of radiation dose from LLNL releases to air: stacks (on buildings containing radioactive materials management areas) and diffuse area sources.[a,b]

Bldg	Facility	Potential emission points	Maximum EDE[c] (μSv/y)	Operations
131	Engineering	4	1.8×10^{-4}	Handling, storing, machining, characterizing, assembling, sorting, and transferring materials; repackaging of waste
151	Isotope Sciences	20	4.5×10^{-7}	Chemical separation, crushing and dissolving, aliquot preparation and storage, gas analysis, radiochemical separations, preparation of radioactive counting standards
166	Pyrochemistry Demonstration Facility	1	0.0[d]	Conversion of uranium to halides and oxides
175	Laser Isotope Separation	6	0.0[d]	Cleaning and refurbishing of uranium parts
177	Laser Isotope Separation	4	6.5×10^{-5}	Sample preparation, cleaning and refurbishing of parts, processing uranium oxide powders
194	Physics & Space Technology	3	2.5×10^{-4}	Accelerator
212	Physics & Space Technology	2	8.0×10^{-11}	Environmental, safety, and health surveillance for shutdown of accelerator
222	Chemistry & Materials Science	21	1.7×10^{-3}	Radioanalytical analyses and tracer use
224	Chemistry & Materials Science	4	4.8×10^{-4}	Waste samples analysis
226	Chemistry & Materials Science	2	5.8×10^{-9}	Radioactive and mixed waste chemical analyses
227	Chemistry & Materials Science	5	2.4×10^{-6}	Uranium bonding and testing
231	Mechanical Engineering	16	1.3×10^{-2}	Materials research and testing, plastics shop work, electron-beam welding
	Mechanical Engineering Vault	1	0.0[d]	Storage, handling, and shipping of radionuclides
235	Chemistry & Materials Science	10	2.7×10^{-7}	Welding, actinide and uranium catalyst research
241	Chemistry & Materials Science	7	3.5×10^{-9}	Materials development, measurement, and testing
251	Heavy Elements			Heavy-element research
	Hardened area	4	0.0[d]	
	Unhardened areas	37	1.5×10^{-4}	
253	Hazards Control	12	5.5×10^{-9}	Radiochemical analyses
254	Hazards Control	5	5.6×10^{-11}	Radiochemical analyses of bioassays
255	Hazards Control	2	1.0×10^{-4}	Instrument calibration
281	Chemistry & Materials Science	9	5.0×10^{-9}	Preparation and storage of radiochemical stock solutions
292	Physics & Space Technology	3	7.3×10^{-5}	Tritium contamination from prior operations
298	Laser Fusion	2	1.3×10^{-4}	Handling and assembly of tritium-filled targets, sputtering uranium
321	Materials Fabrication	5	4.2×10^{-6}	Machining

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Table 13-1. Sources of radiation dose from LLNL releases to air: stacks (on buildings containing radioactive materials management areas) and diffuse area sources[a,b] (continued).

Bldg	Facility	Potential emission points	Maximum EDE[c] (μSv/y)	Operations
322	Mechanical Engineering	1	8×10^{-8}	Cleaning and plating of depleted uranium
327	Mechanical Engineering	1	1.3×10^{-8}	Nondestructive ultrasonic material evaluation
331	Tritium	2	1.7×10^{-1}[d]	Decontamination and decommissioning operations
332	Plutonium	6	0.0[d]	Machining and metallurgy
361	Biological Research	24	1.1×10^{-5}	Radiolabeling; biological dosimetry; DNA sequencing, hybridization, and repair; human genome; enzyme assay; radioactive probes
362	Biological Research	1	2.2×10^{-7}	Dose preparation for animal experiments
363	Biological Research	1	1.9×10^{-5}	Dispensing samples
364	Biological Research	2	6.3×10^{-5}	DNA labeling; isolation and purification
365	Biological Research	1	6.4×10^{-12}	Housing research animals
366	Biological Research	2	2.5×10^{-8}	DNA sequencing; metabolization
378	Environmental Research	2	1.5×10^{-9}	Environmental analysis
381	Laser Fusion	1	2.7×10^{-13}	Tritium handling for laser target research
391	NOVA Laser	1	2.8×10^{-4}	Vaporization of targets
412 W	Health and Ecological Assessment Division	1	2.3×10^{-12}	Sample preparation for measurement of Ni-59 and Ni-63
419	Hazardous Waste Management	2	9.8×10^{-4}[d]	Decontamination and decommissioning
490	Laser Isotope Separation	4	0.0[d]	U.S. Enrichment Corporation operations
491	Laser Isotope Separation	1	0.0[d]	U.S. Enrichment Corporation operations
513	Hazardous Waste Management	3	3.8×10^{-7}	Drum repacking and sludge stabilization
514	See diffuse sources below			
801	Site 300 Firing Table at 801	—[e]	1.2×10^{-1}	Detonation of explosives
851	Site 300 Firing Table at 851	—[e]	8.2×10^{-2}	Detonation of explosives
	Livermore site diffuse sources[f]	6	See next six entries below	Storage areas and contaminated ground
292	Physics & Space Technology	1	1.3×10^{-6}	Tank leakage area
331	Tritium	1	5.9×10^{-2}	Outdoor waste accumulation area
419	Hazardous Waste Management	1	4.6×10^{-4}	Pipe removal as part of tank project
514	Hazardous Waste Management	1	7.2×10^{-3}	Waste treatment and storage

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Table 13-1. Sources of radiation dose from LLNL releases to air: stacks (on buildings containing radioactive materials management areas) and diffuse area sources[a,b] (concluded).

Bldg	Facility	Potential emission points	Maximum EDE[c] (μSv/y)	Operations
	Livermore site diffuse sources[f] (continued)			
612	Hazardous Waste Management	1	1.4×10^{-1}	Waste storage
—	Southeast quadrant of Livermore site	1	9.4×10^{-3}	Contaminated ground
	Site 300 diffuse sources[f]	6	See next six entries below	Contaminated ground and water
—	Pit 7 Complex	1	3.5×10^{-4}	Contaminated ground and purge water
802	Site 300	1	6.2×10^{-7}	Contaminated ground
850	Site 300	1	6.2×10^{-5}	Contaminated ground
851	Site 300	1	2.1×10^{-7}	Contaminated ground
—	Well 8 Spring	1	1.4×10^{-6}	Contaminated spring water
—	Full Site 300 area	1	2.6×10^{-2}	Contaminated ground

a *LLNL NESHAPs 1995 Annual Report* (Gallegos et al. 1996).

b RMMAs in which no operations using radionuclides took place in 1995 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 member of the public (SW-MEI) 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 limit of sensitivity, as discussed in the Monitored Facilities section.

e Open air dispersal in 1995.

f Diffuse sources are described briefly in the section on specifications of source terms, and more fully in the *LLNL 1995 NESHAPs Annual Report* cited in footnote a.

Monitored Facilities

The continuously monitored facilities at LLNL are Buildings 166, 175, 231 Vault, 251, 331, 332, 419, 490, and 491. In 1995 a new sampling system was installed at Building 166, the Pyrochemistry Demonstration Facility, as described in the *LLNL NESHAPs 1995 Annual Report* (Gallegos et al. 1996). Most of the monitored facilities show emission levels below the minimum detection limit (MDL), primarily because of the use of multiple-stage, high-efficiency particulate air (HEPA) filters in all significant release pathways. The efficiency of a single-stage HEPA filter is 99.97%. Double-stage filter systems are in place on some discharge points. Triple-stage HEPA filters are used on glove box ventilation

systems in the Building 332 Plutonium Facility and in a portion of Building 251. In 1995, samples from three emissions points at two of the monitored facilities, Buildings 251 (unhardened section) and 419, yielded results for gross alpha radioactivity greater than the MDL on a majority of the samples collected throughout the year. For a discussion of these results see Chapter 5, Air Effluent Monitoring, in the section entitled "Results: Measured Emissions."

Dose calculations based on actual monitoring data are expected to be more accurate than those using assumptions based on inventory data, physical state release fractions, and emission-control factors. Among the nine continuously monitored facilities at the Livermore site, most do not require monitoring under the EPA 1 μSv/y (0.1 mrem/y) standard. Nonetheless, all of these facilities are continuously monitored for programmatic and other reasons. For example, continuous monitoring is maintained at Building 331 (the Tritium Facility) to provide the most direct and accurate measure of its release of tritium to the atmosphere, even though the EDEs we calculate from measured unabated emissions are below the 1 μSv/y (0.1 mrem/y) level (see **Table 13-1**). As other examples, continuous monitoring is maintained at Building 332 and the hardened portion of Building 251 in lieu of undertaking a modeling and measurement effort that would be required to demonstrate that monitoring is not needed.

Beyond the stack effluent monitoring, site-specific surveillance air monitors are placed in the vicinity of diffuse emission sources on site, such as those (described below) associated with Buildings 292, 331, 514, and 612 and in and around the southeast quadrant of the Livermore site. These special monitors measure the concentrations of radionuclides present in the air near the sources and allow a direct determination of their environmental impact.

Monitoring showed that the amount of radioactivity released from LLNL during 1995 was slightly less than in 1994 and was below the range of earlier years (see Chapter 5; especially **Table 5-3** and **Figure 5-2**).

Inventoried Sources

For unmonitored or noncontinuously monitored facilities, we relied on inventories, together with EPA-specified fractions for potential release to air of materials in different physical states (solid, liquid, powder, or gas), in accordance with 40 CFR Part 61, Subpart H, Appendix D. Use of the state-dependent potential release fraction adjusts (by multiplication) the total annual inventory to give conservative potential annual release to air. If the material was an unconfined gas, then the release fraction 1.0 was used; for liquids and powders, 1.0×10^{-3} was used; and for solids, 1.0×10^{-6} was used. In addition, credit was

taken for radionuclide emission control devices when calculating total dose for evaluation under the 10 mrem / y (100 μSv / y) EPA standard; e.g., EPA allows an emission-reduction factor of 1.0×10^{-2} for each stage of HEPA filtration. However, emissions were assumed to be unabated for evaluations under the 1 μSv / y (0.1 mrem / y) EPA standard for required continuous monitoring.

For 1995, we updated the radionuclide inventories in our Livermore site key facilities, defined as those on a ranked list that contributed to 90% of the 1994 Livermore site radiological dose to members of the public. We also inventoried all RMMAs that began operations in 1995. Inventory forms, accompanied by detailed guidance for completing them, were provided to all of these facilities, filled out by experimenters, and certified by facility managers.

Explosive Tests at Site 300

Modeling releases to the atmosphere from explosive tests at Site 300 requires special attention 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, and disperses as it is carried downwind. (The 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, in which the scaling parameter is the TNT-equivalent explosive mass. Isotopic ratios for depleted uranium are used. The masses of the three uranium isotopes with atomic weights 238, 235, and 234 (occurring in depleted uranium in the weight-percentages 99.8, 0.2, and 5×10^{-4}, respectively) are multiplied by their respective specific activities to get the total number of curies for each isotope in the cloud.

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 low-level, steady-state (year-long), stack-type emission occurring over flat terrain with meteorological data appropriate to annual average conditions at Site 300. An alternative modeling methodology that treats these transient explosive events as short-duration puffs, and that incorporates some of the effects of the hilly terrain at Site 300, was submitted for approval in 1992 (*LLNL NESHAPs Project Quarterly Progress Repor*t, Biermann et al. 1993), but LLNL was directed by EPA to use the CAP88-PC code for these calculations despite the recognized difficulties.

Several conservative assumptions are made in the absence of detailed data: (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 micrometer; (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.

Diffuse Sources

Another category of sources requiring special attention is diffuse emissions, including fugitive emissions. Diffuse, or nonpoint, sources often are difficult to quantify. Presently, methods of dose calculations associated with them are left to the discretion of each DOE facility; LLNL reviewed a second draft of proposed EPA guidance on this topic in 1994.

Four different modeling approaches were used for diffuse sources at LLNL's Livermore site in 1995. Elevated tritium levels in soil moisture near Buildings 292 and 419 required a calculation of the source term and the use of CAP88-PC. Estimated releases from tritium-contaminated equipment outside Building 331 were derived from measurements of surface contamination, process and facility knowledge, and environmental surveillance measurements. Radioactive wastes stored in the Building 612 Yard required environmental surveillance data to estimate emissions. For Building 514, which houses the Hazardous Waste Management tank farm for waste processing and storage, radiological-inventory data were used with standard CAP88-PC modeling techniques. Direct ambient air monitoring of plutonium in surface soils in the southeast quadrant of the Livermore site provided data on which to base dose calculations.

Diffuse sources at Site 300 involve tritium and uranium. Their evaluation was based on data provided in the *Final Site-Wide Remedial Investigation Report Lawrence Livermore National Laboratory Site 300* (Webster-Scholten 1994), where potential routes of tritium and uranium migration from soil to air were identified and evaluated. These radionuclides were components of the explosives assemblies tested on the Site 300 firing tables over many years. Five diffuse sources of tritium (the Pit 7 Complex, Well 8 Spring, and ground areas associated with Buildings 802, 850, and 851) were characterized.

Our method of calculating the diffuse source dose from the resuspension of depleted uranium in soil at Site 300 relies on air emissions monitoring. We have revised our method to eliminate the contribution of naturally occurring uranium to the measured values and to eliminate double-counting due to experiments that occurred during monitoring periods. Descriptions of each diffuse source at the two sites and the assumptions made regarding their emissions are given in the *LLNL NESHAPs 1995 Annual Report* (Gallegos et al. 1996).

Calculated Results Summary—Livermore Site and Site 300, 1995

Table 13-1, as discussed earlier, summarizes the sources of the radiation dose from airborne radionuclides emitted by routine LLNL operations in 1995. In particular, the number of potential discharge points at each facility is given along with the largest EDE value from any one discharge point at each facility. Corresponding information is given for Site 300 facilities and for the diffuse sources at both sites, again referring to releases during routine operations. There were no unplanned atmospheric radionuclide releases at either the Livermore site or Site 300 in 1995.

Table 13-2 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 93% of the total EDE resulting from Livermore site operations and nearly 100% of the total EDE from Site 300 operations. The dominant radionuclide(s) are indicated for each facility. Tritium accounted for about 90% of the Livermore site dose, and uranium (principally uranium-238) for most of the remaining 10%. At Site 300, practically the entire dose was due to the isotopes uranium-238, -235, and -234 that make up depleted uranium.

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. In contrast to previous years when we assumed that all food was locally produced, in 1995 we specified an agricultural option in CAP88-PC in which milk is imported while the remainder of the food is still produced locally. We found that when we used this assumption with the meteorological conditions and source emission characteristics at LLNL in 1995, ingestion remained the most important pathway in the case of tritium, and inhalation was still most important for uranium. However, the numbers changed: Ingestion contributed 82% of the dose for tritium and inhalation accounted for 97% of the dose for uranium, versus 86% and 89%, respectively, under the previous assumptions. For both uranium and tritium, external doses from air immersion and ground irradiation were negligible.

Table 13-2. Major contributors to LLNL's radiation dose via airborne emissions, 1995.

Facility or operation[a]	Dominant radionuclide(s)	EDE at SW-MEI[b]	
		μSv/y	mrem/y
Livermore site			
B331/Tritium Facility	^{3}H	0.17	0.017
B612 Yard Area[c]	^{3}H	0.14	0.014
B331 Exterior[c]	^{3}H	0.059	0.0059
B231	^{238}U, ^{234}U, ^{235}U	0.014	0.0014
Sum of other sources	Various	0.03	0.003
Total		**0.41[d]**	**0.041[d]**
Site 300			
B801/firing table	^{238}U, ^{234}U, ^{235}U	0.12	0.012
B851/firing table	^{238}U, ^{234}U, ^{235}U	0.082	0.0082
Soil resuspension[c]	^{238}U, ^{234}U, ^{235}U	0.026	0.0026
Total		**0.23[d]**	**0.023[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 13-1**, which represent the dose from the single largest emission point on each facility. The sitewide maximally exposed individual member of the public (SW-MEI) 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 0.4% and 0.2%, respectively, of the federal standard.

Maximum Dose to an Individual Member of the Public

The calculated EDE to the SW-MEI at the Livermore site in 1995 was 0.19 μSv (0.019 mrem) from point source emissions and was 0.22 μSv (0.022 mrem) from diffuse source emissions. Summing these contributions yields a total dose of 0.41 μSv (0.041mrem) for the Livermore site in 1995—46% from point sources, 54% from diffuse sources. The leading contributors to dose were 41% of the total from the two 30-m stacks at the LLNL Tritium Facility (Building 331), 34% from the Building 612 Yard diffuse source, and 14% from the Building 331 Waste Accumulation Area. No other source contributed more than 3% to the dose.

The total dose to the SW-MEI at Site 300 during 1995 was calculated to be 0.23 μSv (0.023 mrem). Explosive tests at the Building 801 and Building 851 firing tables accounted for all of the point source dose of 0.20 μSv (0.020 mrem), while a source representing resuspension of LLNL-contributed uranium in surface soils throughout the site was responsible for nearly all of the diffuse sources total of 0.03 μSv (0.003 mrem).

Table 13-3 shows the dose values from firing table experiments for 1990 through 1995, correlated with the total amounts of depleted uranium and the total quantity (TNT-equivalent) 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 13-3. Annual dose to the SW-MEI from explosives experiments on firing tables at Site 300, 1990–1995, 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 (μSv)	Dose to SW-MEI (mrem)	Total depleted U used in experiments (kg)	Total HE used in depleted U experiments (kg)
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

The trends in dose to the SW-MEI from emissions at the Livermore site and Site 300 over the last 6 years are shown in **Figure 13-2** and **Table 13-4**. The levels of public exposure indicated in this figure and table are well below the EPA standard, which limits the whole-body air-pathway EDE to members of the public from DOE activities to 100 μSv / y (10 mrem / y).

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 for releases to air: ingestion through food and water consumption, inhalation, air immersion, and irradiation by contaminated ground surface.

Population distributions centered on the two LLNL sites were compiled from 1990 census data. Our population data files, specifying the distribution of population with distance and direction, are tabulated in the *LLNL NESHAPs 1995 Annual Report* (Gallegos et al. 1996) Key population centers affected by LLNL

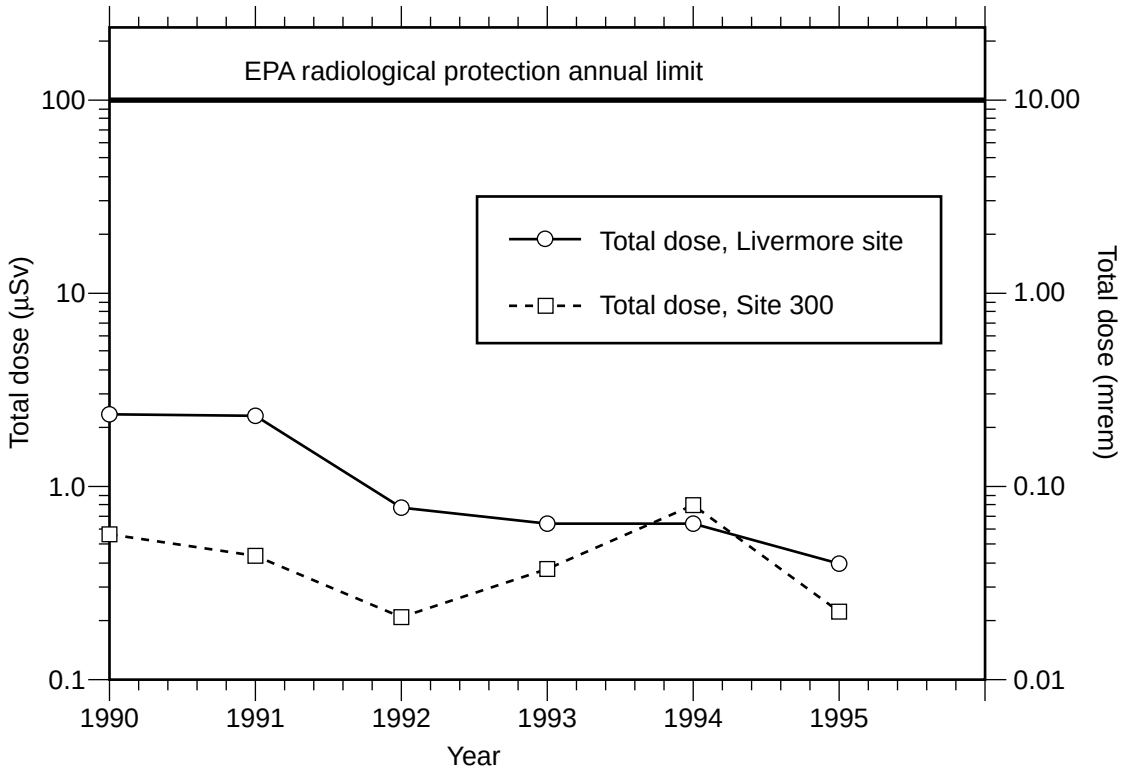

Figure 13-2. Dose to the sitewide maximally exposed individual member of the public, 1990 to 1995.

emissions are the relatively nearby communities of Livermore and Tracy, and the more distant metropolitan areas of Oakland, San Francisco, and San Jose, as well as the San Joaquin Valley communities of Modesto and Stockton. Within the 80-km outer distance specified by the EPA, there are 6.3 million residents included for the Livermore site collective dose determination, and 5.4 million for Site 300. (Because the two sites are separated by 24 km, some of the residents are common to both determinations.)

The collective EDE due to 1995 Livermore site operations was 0.0059 person-Sv (0.59 person-rem), of which 0.0038 person-Sv (0.38 person-rem), or 64%, was from point-source emissions and the remaining 36% from diffuse sources. This value is slightly less than the 1994 result of 0.0076 person-Sv (0.76 person-rem). The corresponding collective EDE from Site 300 operations in 1995 was 0.077 person-Sv (7.7 person-rem), composed of 0.72 person-Sv (7.2 person-rem), or 94%, due to point-source emissions, and 0.005 person-Sv (0.5 person-rem) from diffuse-source emissions. The total collective EDE value is less than half the 1994 value of 0.17 person-Sv (17 person-rem) but is very similar to the 1993 value of 0.069 person-Sv(6.9 person-rem). Year-to-year differences result primarily

Table 13-4. Doses (in μSv) calculated for the site-wide maximally exposed individual for the Livermore site and Site 300, 1990 to 1995.

Year	Total dose	Point source dose	Diffuse source dose
Livermore site			
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	—[a]	—[a]
1990	2.40	—[a]	—[a]
Site 300			
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.

from differences in the amount of high explosives used in experiments at Site 300. In 1995, our more realistic treatment of the Site 300 diffuse-source contribution from resuspension of uranium in the soil lowered the population dose by about 0.02 person-Sv (2 person-rem).

The larger collective dose (vis-à-vis individual dose to the SW-MEI) for Site 300 relative to that for the Livermore site is traceable primarily to our highly conservative assumptions used in modeling the Site 300 explosives experiments. As described in the section above on "Explosive tests at Site 300," these assumptions concern especially the height and trajectory of the explosive-debris cloud, the fraction of radioactive material that is aerosolized, and the lung clearance class assumed for inhaled material. For example, the scaling laws used to set initial conditions for the explosive debris cloud typically give cloud heights of about 200 m and diameters of about 20 m. Calculations show that such highly elevated, large clouds are readily carried long distances to reach population centers downwind, compared to emissions from even the large stacks at LLNL's Tritium Facility, which have 30-m stack heights and stack diameters of order 1 m.

We note that the diffuse sources influence the individual dose to the SW-MEI more than they impact the population dose. The reason is the relatively less dynamic nature of the diffuse-source emissions, originating low to the ground at low initial velocity, producing peak concentrations near the site.

13. Radiological Dose Assessment

Summary and Conclusion

The annual radiological dose from all emissions at the Livermore site and Site 300 in 1995 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 maximally exposed public individual was found to be 0.41 μSv (0.041 mrem) from Livermore site emissions and 0.23 μSv (0.023 mrem) from Site 300. 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 for LLNL 1995 operations was calculated to be 0.0059 person-Sv (0.59 person-rem) from Livermore site operations and 0.077 person-Sv (7.7 person-rem) from Site 300. These doses include exposed populations of 6.3 million people for the Livermore site and 5.4 million for Site 300, living within a distance of 80 km from the site centers, based on 1990 census data.

Table 13-5 compares the individual and collective radiation doses from atmospheric emissions 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 8000 times smaller the doses from background radiation (see also **Figure 13-1**), and the population dose from LLNL operations is about 200,000 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. Thus, the maximum credible doses show that LLNL's use of radionuclides had no significant impact on public health during 1995.

Table 13-5. Comparison of background and LLNL radiation doses, 1995.

Location/Source	Individual dose[a]		Population dose[b]	
	(μSv)	(mrem)	(person-Sv)	(person-rem)
Livermore site sources				
Atmospheric emissions	0.41	0.041	0.0059	0.59
Site 300 sources				
Atmospheric emissions	0.23	0.023	0.077	7.7
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 1987).

d These values vary with location.

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