

APPENDIX D. SUPPLEMENTARY TOPICS ON RADIOLOGICAL DOSE

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D-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 other 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 less air is overhead to act as a shield. 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 because of 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, energy production, and nuclear weapons production. 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 1986 nuclear reactor accident at Chernobyl 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 and smoke detectors.

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. There are three main categories of nuclear decay: 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 sponta-

* The National Cancer Institute provides a calculator of dose and risk for people in the continental United States exposed during the 1950s and 1960s to iodine-131 from nuclear weapons tests at the Nevada Test Site. The calculator is available at:
<http://nts131.nci.nih.gov/default.asp>

neous 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, a stable isotope.

Radioactivity can be hazardous because radiation (alpha particles, beta particles, gamma rays, and other subatomic particles such as neutrons) 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, being significantly attenuated only by thick slabs of dense materials, such as lead.

Measurement of Radioactivity and Dose

The rate at which a nucleus decays is expressed in either units of becquerels (abbreviated Bq) where 1 Bq is one decay per second, or alternatively in curies (abbreviated Ci), where 1 Ci equals 3.7×10^{10} (37 billion) decays per second, or 3.7×10^{10} Bq. (This is 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; the effect on living tissue 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; 1 Gy

equals 1 joule per kilogram. 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) with 1 Sv equal to 100 rem. Also commonly used are millirem (mrem) and 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 are others; therefore, the different parts of the body are given weightings. For example, a 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” (EDE), also expressed in rem or sievert. This allows dose equivalents from nonuniform exposure of the body to be expressed in terms of an EDE that is numerically equal to the dose from uniform exposure of the whole body that entails the same risk as the nonuniform exposure.

The EDE describes doses to individuals. When individual EDEs 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 appendix deals with the EDE and the collective EDE.

Doses from Natural and Man-Made Radioactivity

Annual average radiation doses from natural and other common sources in the United States have been estimated by the National Council on Radiation Protection and Measurement (1987b). The average radiation dose from natural sources 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 ingested through food and drink, resulting in approximately 0.4 mSv/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 inhalation dose is dominated by radon’s short-lived decay products.

As noted earlier, 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. Nuclear medicine contributes 0.14 mSv (14 mrem) to the average dose, and consumer products add 0.1 mSv (10 mrem). Thus, for a typical member of the public in the United States, radiation from medical procedures and consumer products results in a dose of approximately 0.63 mSv/y (63 mrem/y). The annual average

dose from other man-made sources, including fallout from nuclear testing, is less than 0.03 mSv (3 mrem). As described in Chapter 13, the contributions from LLNL operations to the dose of even the most affected resident are on the order of 1 μ Sv/y (0.1 mrem/y), which is a small fraction of the average doses from natural and man-made radioactivity (see Table 13-5).

Deviations from the average levels can be quite large, depending on an individual's place of residency, occupation, eating habits, and other lifestyle choices, such as frequency of air travel. Radon dose, for example, varies significantly with geographic location; levels several times higher than the average occur in some regions of the United States. At LLNL and its environs, radon-induced doses as low as half the average are typical. Doses from cosmic rays increase with elevation above sea level, producing several tenths of mSv (tens of mrem) differences between cosmic-ray doses in coastal and mountain communities, and imparting a dose of about 0.05 mSv (5 mrem) to a passenger flying round-trip between Los Angeles and New York City.

A useful Internet reference with links to a large quantity of material on effects and risks from radiation is the "Radiation Information Network" at the following Internet address:

<http://www.physics.isu.edu/radinf/>.

D-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. More detailed

information can be found in LLNL's online *ES&H Manual*; see, for example, Documents 2.1 and 2.2 at the following Internet addresses:

http://www.llnl.gov/es_and_h/hsm/doc_2.01/doc2-01.html

http://www.llnl.gov/es_and_h/hsm/doc_2.02/doc2-02.html

When an operation or facility is designed at LLNL, 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. Work places 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-filtered stacks, stacks without abatement devices, roof vents, and ordinary room air ventilation channels.

Appropriate monitoring, control, training, emergency response, and other requirements are called out in various facility documents related to each operation. These may include a discipline action plan (DAP), Integration Work Sheet (IWS), safety analysis report (SAR), operational safety plan (OSP), and/or facility safety plan (FSP), and will include a document reviewing the operation under the NEPA compliance guidelines. These documents are reviewed by environmental analysts, industrial hygienists, and health physicists to assess the safety of the operation, its compliance with current occupational and public health and environmental standards, the adequacy of proposed engineering and administrative controls, and the adequacy of proposed 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 monitoring includes sampling of the air and surfaces in the facilities where radioactive materials are handled, as well as the use of personal dosimetry and bioassay programs to monitor potential worker exposure to direct radiation and radioactive isotopes. Direct monitoring of the workplace environment 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, ground and surface waters, sewerable water, soil and sediment, and vegetation and food-stuff, 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 they directly gauge the degree of success of LLNL's radionuclide discharge control program in limiting exposures of the public. LLNL implemented a quality assurance/quality control (QA/QC) process to ensure the accuracy, precision, and reliability of these monitoring data (see [Chapter 14](#)).

In addition to routine QA/QC measures carried out each year, special audits by outside agencies and self-assessments are performed occasionally. Examples are the audit by DOE's Office of Independent Oversight and Performance Assurance of LLNL's environment, safety, and health (ES&H) and emergency management programs in June 2002, the public health assessments conducted by the Agency for Toxic Substances and Disease Registry (ATSDR) at the Livermore site in the 1999-2002 time frame, and the self-assessment of LLNL's NESHAPs Program by the Laboratory's Assurance Review Office (ARO) conducted during 1999 and 2003.

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 the Laboratory's assessments provide the best information possible regarding the radiological impact of its operations.

