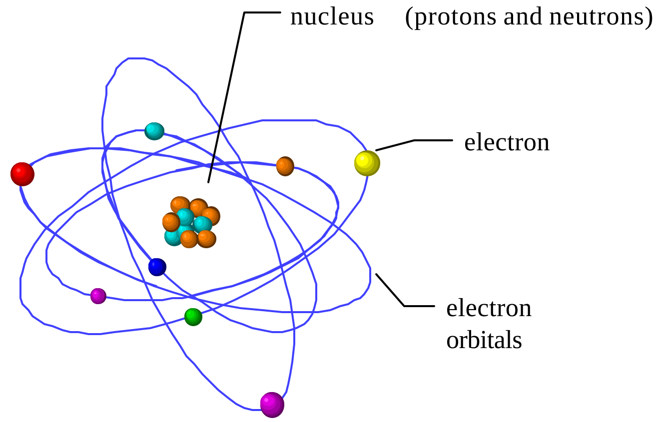
APPENDIX F

PRINCIPLES OF RADIATION

The Atom

All substances are composed of atoms. Atoms are exceedingly small with an average diameter of only about 0.000,000,001 inch. To put this in perspective, approximately 100,000 atoms lying side by side in a straight line touching one another would span the thickness of a sheet of thin paper. Atoms are composed of three basic parts:

- electrons,
- protons , and
- neutrons



Atom Model

Protons and neutrons compose the part of an atom called the nucleus. The protons have a positive electrical charge while the neutrons have no electrical charge. Protons and neutrons are similar in mass and are considerably more massive than electrons (approximately 1,800 times as massive). Therefore the nucleus contains nearly all of the mass of the atom. The electrons, which carry a negative electrical charge, orbit the nucleus. Typically, the number of protons (positive charges) in the nucleus is equivalent to the number of electrons (negative charges) in the orbits, thus creating an atom that is electrically neutral (no net charge).

The atomic number is an identifying characteristic of an element and equals the number of protons in the atomic nucleus of an atom. Each element has an associated atomic number that serves as an identifier. For example, hydrogen has an atomic number of one corresponding to one proton in the nucleus (the hydrogen atom also has an electron that orbits the nucleus thus keeping the atom electrically neutral). Plutonium, a much more massive atom, has an atomic number of 94 corresponding to 94 protons in the nucleus and 94 electrons orbiting the nucleus to maintain electrical neutrality.

The sum of the protons and neutrons in an atom’s nucleus is called the mass number. Although the number of protons in the nucleus will always be the same for any given element, the number of neutrons in the nucleus can vary. For example, most hydrogen atoms have a nucleus composed of a single proton with no neutrons giving it a mass number of 1. Hydrogen atoms with mass number two are known as deuterium and have both a proton and a neutron in the nucleus. Tritium, a form of hydrogen important to past MEMP operations, has a nucleus composed of one proton and two neutrons. As can be seen from this example, all three forms of hydrogen have exactly one proton in the nucleus, but have differing numbers of neutrons. Chemically, these three forms of hydrogen all behave in a similar manner. These forms of hydrogen all having the same atomic number but different mass numbers are known as isotopes.

The radionuclides that are of concern at MEMP are:

Radionuclide	Mass Number	Half-Life (years)
plutonium-238	(94 protons + 144 neutrons = mass number 238)	87.7
plutonium-239	(94 protons + 145 neutrons = mass number 239)	24,100
plutonium-240	(94 protons + 146 neutrons = mass number 240)	6,560
uranium-233	(92 protons + 141 neutrons = mass number 233)	1.6×10^5
uranium-234	(92 protons + 142 neutrons = mass number 234)	2.5×10^5
uranium-235	(92 protons + 143 neutrons = mass number 235)	7.1×10^8
uranium-238	(92 protons + 146 neutrons = mass number 238)	4.5×10^9
thorium-228	(90 protons + 138 neutrons = mass number 228)	1.9
thorium-230	(90 protons + 140 neutrons = mass number 230)	7.5×10^4
thorium-232	(90 protons + 142 neutrons = mass number 232)	1.4×10^{10}
hydrogen-3 (tritium)	(one proton + two neutrons = mass number 3)	12.3

Radioactivity and Radiation

The atomic nucleus is held together by exceedingly strong forces of attraction which act indiscriminately between its protons and neutrons, protons and protons, neutrons and neutrons. Certain isotopes, because of their own physical makeup, are unstable. This instability is due to an unbalanced ratio between the number of protons and the number of neutrons. This instability in the nucleus causes the atom to change spontaneously to a more stable, less energetic state. This spontaneous change is called radioactivity and the atom is said to decay or disintegrate. Radiation is the particles and energy associated with the radioactivity. The three major types of radiation are alpha, beta, and gamma.

When a radioactive atom decays, its nucleus changes and the resultant atom generally is no longer the same kind of atom; it transforms into an element of different atomic number. As noted above, the radioactive decay is brought about by instability in the nucleus. By the process of radioactive decay the atom strives to achieve a more stable configuration. The ultimate stable configuration is not always reached in decay transformation. In fact, the new element, called a "daughter" resulting from the radioactive decay may be more unstable than the "parent." Ultimately the original radionuclide will be transformed into a stable element through a series of transformations. The decay sequence from radioactive parent to radioactive daughter is called a radioactive decay chain. The time required for one-half of all the atoms of a radionuclide to decay is called its "half-life." The half-life is an average value for any very large number of atoms. It does not accurately apply to a small number of atoms.

Each atom essentially takes its own time to decay and there is no predicting when its instability will cause it to do so. Radionuclides with short half-lifes such as iodine-131 (used in medical radiotherapy) decay away rapidly and may not pose as much of an environmental concern as a long lived (long half-life) radionuclide like plutonium-239 which may remain in the environment for many thousands of years.

As noted above, there are three primary types of radiation:

- alpha
- beta
- gamma

Alpha particles result when the unstable nucleus of a radionuclide ejects a particle consisting of two protons and two neutrons. The resulting particle has a net positive charge and will therefore react with any atoms that are nearby (i.e. with the negative electronic charges of the orbital electrons or the positive electronic charge of the protons in the nucleus). These interactions cause the alpha particle to give up some of the original energy it contained when ejected from the nucleus. In fact there are enough atoms within the thickness of an ordinary sheet of paper to react with and bring to rest most alpha particles. The alpha particle will therefore not penetrate solid material to any significant depth. If an alpha particle is released inside the human body (by means such as inhaling radioactive particles), the emitted alpha particle will be brought to rest rapidly within a small volume of human tissue. Thus all of the energy of the alpha particle is released within a small volume of tissue and cellular damage can occur. Isotopes of plutonium and uranium are examples of radionuclides used by MEMP that decay by emitting alpha particles.

Beta particles result when the unstable nucleus of a radionuclide ejects a particle consisting of a negatively charged electron. As with alpha particles, the charged beta particle interacts with any atoms that are nearby thus losing some of its initial energy. However, because beta particles have only half the charge of an alpha particle and are ejected from the nucleus with a much greater velocity, most can penetrate solids more readily than alpha particles. Tritium is an example of a radionuclide used by MEMP that decays by emitting a very low-energy beta particle.

Gamma rays, unlike alpha and beta particles, are not physical particles. Instead a gamma ray is a package of energy that behaves as though it were a particle. Gamma rays are exactly the same in nature as visible light, heat waves, radio waves, radar rays and x-rays. They have very short wavelengths that are typically shorter than those of most x-rays and are generally more energetic than x-rays. The penetrating power of x-rays is well known and since gamma radiation is very much like the radiation of x-rays, the penetrating power of gamma radiation is also very high. Gamma rays can pass through the human body giving up small amounts of energy along the way. Many radionuclides emit both alpha and gamma or beta and gamma radiation upon decay. Isotopes of plutonium are examples of radionuclides used by MEMP that decay by emitting both alpha and gamma radiation.

Units of Measurement

Radioactivity is typically measured in terms of "activity." Activity corresponds to the number of atomic nuclei of any particular radionuclide that decay over a specified time interval. A "curie" (Ci) is a unit typically used to define activity. One curie is equal to the amount of radioactive material that decays at a rate of 37 billion atoms per second. This disintegration rate is almost exactly the rate at which one gram of radium-226 decays. As noted earlier, each radioactive isotope follows its own specific decay schedule in accordance with its half-life. As a result, for a given quantity of material (e.g. one gram), different radionuclides will vary in the number of nuclei that will disintegrate over a given time period. Therefore equal masses of different radionuclides have varying activity levels that are dependent on each radionuclide's half-life. As an example, one gram of radium-226 (radium-226 has a half-life of 1,600 years) is equivalent to one curie of activity. It would take about 1.5 million grams of uranium-238 (half-life 4.5 billion years) to have an activity of one curie. In other words it would take 1.5 million grams of uranium-238 to yield 37 billion disintegrations per second. As can be seen from the example, radionuclides that decay rapidly (short half-lives) have relatively high activity levels compared to radionuclides that have very long half-lives.

It should be noted that a curie is only related to the number of disintegrations that occur in a given time frame and does not indicate the biological damage that the radionuclide could cause if it comes into contact with a person. That is to say that one curie of tritium is not equivalent to one curie of plutonium-238 in terms of the biological effect on living tissue. The activity levels of radionuclides in the environment due to MEMP activities operations are typically very small fractions of a curie. A convenient way to express these very small curie fractions is introducing two additional units: the microcurie (μCi) (one millionth of a curie) and the picocurie (pCi) (one trillionth of a curie). These units are used throughout this Report.

Radiation Dose

Radiation dose is a measure of the amount of energy delivered to a body. As noted in the previous section, for a given activity level, different radionuclides will vary in their ability to cause biological damage (e.g., at a given activity level, alpha radiation is more damaging than beta). A "dose equivalent" is a means of comparing the dose resulting from exposure to various radionuclides. The Roentgen Equivalent Man (rem) is the unit used to express the dose equivalent. A rem is defined as the dose, measured in terms of a specific amount of energy, which produces the biological equivalent to that produced by the same amount of x-ray energy. The rem allows for a direct comparison of the potential damage that may be caused by exposure to various radionuclides. The higher the rem value, the greater the potential for biological damage.

Dose can be viewed in several different ways and is typically reported with respect to either a specific organ, an effective dose, a committed effective dose, or a whole body dose. Each dose measure will be discussed below.

The ***organ dose*** is the estimated dose received by a specific organ due to exposure to radiation. Certain radionuclides may tend to accumulate within specific organs of the body. Critical organs can be identified based on the chemistry of the radionuclide, the amount of radiation, the sensitivity of the organ to radiation, and the importance of the organ to the body.

The ***effective dose*** estimates the health risk that a radiation dose poses to an individual. The effective dose is calculated by summing the weighted organ dose for each organ. The weighted organ dose is simply the original calculated organ dose multiplied by an importance factor that takes into account the relative risk to the exposed organ.

Some radionuclides assimilated into the body can remain in the body for long periods of time. When particulate material (e.g., dust) contaminated with plutonium is breathed, the plutonium is deposited in the lung tissue. The plutonium will slowly be removed from the body - the original quantity will be reduced over time due to radioactive decay and biological factors. The plutonium is continually emitting alpha and gamma radiation while in the body. The individual is therefore exposed to this radiation for the remainder of his life (or approximately 80 years).

The ***committed effective dose equivalent*** indicates the total dose over the individual's projected remaining lifetime (assumed to be 50 years) which results from an intake during one year. The committed effective dose equivalent (CEDE) expresses the dose of internal radiation received when an individual has ingested, inhaled or absorbed a radionuclide that will remain inside the body. It is also expressed in rem or Sieverts.

Dose Due to Exposure to Background Radiation Sources

Every day our bodies absorb ionizing radiation. Most of it comes from natural sources. Consumer products and medical procedures that use radiation are other common sources of ionizing radiation.

Natural Sources. Natural radiation comes from two sources: cosmic and terrestrial. Cosmic radiation results when energetic particles from outer space, traveling at nearly the speed of light, collide with nuclei in our atmosphere, creating showers of radioactive particles that continue towards earth. The average annual dose equivalent received from cosmic radiation is 26 mrem for an individual living at sea level. Because cosmic radiation dissipates as it travels through the atmosphere, individuals living at lower altitudes receive less dose from this source than those living at higher altitudes.

Terrestrial radiation results when radionuclides that are a natural part of the earth's rocks and soils emit ionizing radiation. Because the concentrations of these radionuclides vary geographically, an individual's exposure depends on his location. The average annual dose equivalent from terrestrial radiation for an individual living in the U. S. is 28 mrem.

Besides absorbing radiation from external radionuclides, we can also absorb radiation internally when we ingest radionuclides along with the food, milk, and water we ingest or along with the air we inhale. Once in our bodies, radionuclides follow the same metabolic paths as nonradioactive forms of the same elements (if there is one). The length of time a particular radionuclide remains and emits radiation depends on whether the body eliminates it quickly or stores it for a long period, and on how long it takes for the radionuclide to decay into a nonradioactive form. The principal source of internal exposure in the U. S. is believed to be radon. Inhalation of radon contributes about 200 mrem to the average annual dose equivalent from internal radiation. Other radionuclides present in the body contribute approximately 39 mrem.

Consumer Products. Many familiar consumer products emit ionizing radiation. Some must emit radiation to perform their functions, e. g., smoke detectors and airport x-ray baggage inspection systems. Other products, e.g., TV sets, emit radiation only incidentally to performing their functions. The average annual effective dose equivalent to an individual from consumer products ranges from 6 to 12 mrem.

Medical Uses. Radiation is a tool for diagnosing and treating disease. The average annual dose equivalent for an individual in the U. S. from medical uses of radiation, not including therapeutic uses, is 53 mrem.

Radiation Environment at MEMP

On average the annual radiation dose due to background radiation to a person living in the United States is about 300 millirem. The total contribution to this dose due to MEMP activities in 2000 was 0.18 mrem, or a very small fraction of the dose received from background.

MEMP's dose contribution for 2000 was well within all applicable guidelines, limits, and regulatory standards. These guidelines, limits and standards are levels which present very low risk to individuals near the site. MEMP, like all DOE sites, strives to keep worker and public doses as low as reasonably achievable.