Technically Speaking

Radioactive Isotopes

by John Nordin, PhD

The PEAC tool user has the option of selecting "radioactive isotopes" when the prompt, "Lookup By" is displayed on the screen. When this option is selected, a list of radioactive elements followed by numbers is displayed on the screen. The user then makes a selection for the particular radioactive isotope, for example, Cesium 137. Information is then displayed about this particular radioactive isotope. Let's spend a little time examining this information and what it means.

Some Basics: What is Radioactivity?

Everything we see around us, even gases that we don't see, is made up of atoms. Atoms each have a central nucleus which is basically made up of protons and neutrons, which account for almost all of its mass. Electrons circle about the central nucleus in various orbits. The number of protons in the nucleus determines the atom name or element. For example, the element hydrogen has one proton, helium has two, lithium has three, up to uranium which has 92 protons. Some man-made atoms have more than 92 protons, for example, plutonium has 94. Protons have a positive charge and normally must be balanced with an equal number of electrons which have a negative charge. If the atom is short one or two electrons or has an excess of electrons, the atom is said to be ionized; this is not the same as radioactivity. Atoms arrange in various combinations to form what we see in the world around us. For example, ordinary table salt is sodium chloride (abbreviated $NaCl$); sodium chloride is made up of one atom of sodium and one atom of chlorine.

Now what is radioactivity? For the nucleus to be stable it must have the right number of neutrons to match up with the number of protons. If there are too many neutrons or too few, the nucleus will shed some of its excess mass. A very small amount of this mass is converted to energy in the process [remember Einstein's formulae $E = mc^2$]. There are several ways that an atom can shed its excess mass. One way is that a neutron can convert to a proton shedding the excess mass as a beta particle. Another way is that two protons and two neutrons can be expelled together as a unit, called an alpha particle. The energy released is partly represented by the kinetic energy of the particles ejected and partly in the form of gamma rays. X-rays and ultraviolet radiation may also be produced, but they are less energetic (and less damaging) than gamma rays.

Now what happens of the alpha or beta particles or the gamma radiation collide with another atom? This excess energy has to go someplace. The atom will probably ionize (shed or add electrons) and heat up. If enough radiation is absorbed by the object, the temperature will increase. Atoms forming part of human flesh will ionize; if the radiation dose is great enough, the person will also experience burns. The ionization also disrupts the human cell function, perhaps enough that the cell could become cancerous. The disruption may occur due to direct action of radiation with the cells of the body or action with water creating unstable, toxic molecules which then damage the cell structure. The term "ionizing radiation" is used to describe this radiation that interacts with other matter (e.g. living tissue).

How are radioactive isotopes made? The radioactive isotope may be man made or may occur naturally. The nucleus of the atom may be bombarded with a neutron or an alpha particle forcing it to absorb the extra mass (as in a nuclear power plant or in the laboratory). Cosmic rays and gamma radiation coming in from outer space may collide with atoms on the earth making them radioactive (e.g. carbon 14) or cause them to ionize. Some radioactive elements are left over from the time when the earth was formed.

What Do Those Numbers Mean, e.g. Cesium 137?

Every radioactive element listed in the PEAC tool has a number after it, e.g. Cesium 137 (abbreviated Cs 137). Sometimes this number will appear as a superscript (e.g. ^{137}Cs) or with another number, (e.g. $^{137}{}_{55}$Cs). The number "137" is the atomic mass number, and is defined as the number of neutrons and protons in the nucleus. If two numbers are shown with the element, the smaller number is the number of protons and the larger number is the number of protons plus neutrons. Since the number of protons are unique to each element (e.g. cesium always has 55 protons, radium always has 89 protons, etc.), the smaller number is usually not stated.

The atomic mass number is an important part of the description of the radioactive isotope. Each radioactive isotope will undergo radioactive decay in a unique way (e.g., emit alpha and/or beta particles of a characteristic energy, or emit gamma radiation of characteristic energies). If the radioactive isotope and quantity released is known, the radiation effects and lifetime can be predicted. Conversely, if the radiation energies are measured with instrumentation, the isotope might be identified, and therefore the possible source (as in the case of a "dirty bomb").

Only the element itself is listed. Cesium 137 could be in the form of cesium chloride or cesium hydroxide. Uranium could be in the form of uranium metal, uranium oxide, uranium hexafluoride, etc. The radioactivity does not depend upon what the compound is. The compound will affect the melting point, boiling point, chemical reactivity, physical appearance, whether the material is a gas or solid but not its radioactivity.

What Radiation Dose is Safe?

The unit of radiation dose is the "rem". "Rem" is an acronym for roentgen-equivalent-man. A "rem" is that quantity of any type of ionizing radiation which when absorbed by a person produces a dose equivalent to the absorption of one roentgen of x-ray or gamma radiation. The radiation from a thermal neutron source is more damaging, about 20 times that of one-roentgen from a gamma ray source. Ionizing radiation includes alpha and beta particles as well as gamma and x-rays, and thermal neutrons. The term "ionizing" refers to what happens when radiation interacts with body tissue; if severe enough it could result in a later cancer or even death.

Another unit of radiation dose is the Sievert, or Sv. One Sievert = 100 rem.

Also 1000 mrem = 1 rem.

Sometimes radiation doses are expressed in "rad" or "gray". The abbreviation for gray is Gy. One Gy = 100 rad. When dealing with whole body radiation from gamma rays, x-rays, and beta radiation, Rad = rem, and Sv = Gy. Alpha particles and neutrons are considered more detrimental when interacting with human flesh so this relationship is no longer true.

The U.S. National Council on Radiation Protection recommends a 5 rems whole body exposure limit in any one year for adult workers who may be in contact with radiation. This is over and above the natural background radiation which everyone is exposed. This radiation dose is accumulative. If “N” is the age of the adult (over 18 years old), the maximum accumulative whole body radiation recommended is (N-18)x5. The maximum radiation exposure for persons under 18 years old is 0.1 rems/year. For pregnant women, the maximum recommended dose is 0.5 rems during the gestation period. Higher doses are allowed for certain body parts such as skin or hands. For skin, a dose of 15 rems is allowed in one year. For hands, a dose of 75 rems is allowed in one year.<

Exceptions are allowed for emergency, life-saving procedures. A person older than 45 years old might “safely” receive a 100 rems one-shot dose plus an additional 200 rems dose on the hands and forearms. This is a one-time deal. The person can’t go into the contaminated zone again even at a later date and receive another 100 rem dose without adverse consequences. The age limit is there because of uncertainties of possible cancer much later in life. A younger person might develop cancer several decades later in life whereas an older person might die from other causes. Background Radiation

Everyone is subject to some natural background radiation. The radiation may be from primordial sources, that is, elements and their decay products left over when the earth was formed. The principal culprit is radon gas formed from the decay of uranium. The second source is from cosmic ray interactions. A third source is human produced or is a result of human actions, for example, from medical diagnostic procedures or from flying at high altitudes. Nuclear power plants account for less than 1% of the total background radioactivity.

A typical annual effective dose of background radiation in the United States is about 360 mrem [0.36 rem]. Of that total, about 200 mrem [0.2 rem] is from inhaling radon gas. Cosmic radiation dose at 1000 foot elevation is about 30 mrem/year. Artificial sources including medical diagnosis procedures accounts for about 60 mrem/year. A person at 15,000 feet would receive five times the cosmic radiation dose rate than at 1000 feet. The remaining natural radiation comes from natural terrestrial radiation and from internally deposited radionuclides in the body. Effects of Radiation Exposure

A person receiving even a fatal dose of radiation may experience no adverse symptoms at the time of exposure. The detrimental effects come later. The radiation dose is roughly accumulative; e.g. four 25 rem doses on different days add up to one 100 rem dose. The accumulation rule is not firm, as a 5 rem dose each year over the course of 40 years is probably less detrimental than a single one-time 200 rem dose (the human body repairs itself over time).

Table 1: Whole Body Radiation Exposure Levels and Resulting Effects for a Single Dose

Dose, Rem	Effects
5	No observable effects
10	Difficult to demonstrate a higher incidence in fetal abnormalities or cancer effects below 10 rem dose. A 10 rem dose results in a 0.8% lifetime increase in developing cancer.
15	Threshold, blood and sperm abnormalities seen
25	Threshold, genetic effects demonstrated

70	A decrease in lymphocytes in peripheral blood chemistry profile after 24 hours indicating some bone marrow depression.
100	Hospitalization recommended
100	Acute symptoms include nausea, malaise, vomiting, and anorexia. Long term effects include a 5% cancer increase death risk, 1% genetic risk defects. The onset of acute symptoms vary with the individual but could be a few days at the low end of the dose (100 rem) or maybe an hour for doses above 200 rem. Most patients are without symptoms below 100 rem.
120	Abrupt decreases in sperm count, but recovery of natural fertility usually occurs after several months or a year
200	Bone marrow depression symptoms apparent. The onset of symptoms associated with bone marrow depression can vary with the individual and dose; but can be several weeks or even months after radiation exposure. These symptoms may occur weeks after the person has recovered from the initial onset of nausea and anorexia. Changes in the peripheral blood profile may occur as early as 24 hours after radiation exposure. Lymphocytes will be depressed most rapidly, and other leukocytes and thrombocytes will be depressed less rapidly. A 50% drop in lymphocytes in 24 hours indicates significant radiation injury. Symptoms include bleeding (hemorrhage) and anemia, diarrhea, fluid loss, and decreased resistance to infection, which become apparent several weeks after radiation exposure. Minimal treatment includes fluid replacement, antibiotics, and prevention of infection. More aggressive treatment includes bone marrow resuscitation therapy.
250	10% of people develop cataracts within several months
300	Epilation (hair loss)
350	Median lethal dose of radiation that will kill 50% of the exposed persons within 60 days without appropriate medical treatment. Mortality is low with aggressive therapy.
400	Continued loss of epithelial cells of the intestinal mucosa results in hemorrhage and marked fluid loss contributing to shock; these symptoms occur within 1 or 2 weeks after irradiation.
600	Almost 100% fatal within 60 days if untreated. Erythema occurs. Lymphocyte count decreases from normal level of about 2000 or 2500 to about 500 in 24 hours. Cognitive impairment.
800+	Rapid incapacitation. Symptoms may occur within an hour after exposure. Diarrhea, fever, electrolyte imbalance. Mortality rate high even with treatment.

2000	Onset of symptoms within minutes. Neurovascular symptoms occur within several hours to about 3 days after exposure. These include a steady deteriorating state of conscience with eventual coma and death.

The above table was constructed from the following two documents:

- Medical Management of Radiological Casualties, 2nd edition, April 2003. Armed Forces Radiobiology Research Institute, Bethesda MD. A copy may be obtained from http://www.afrri.usuhs.mil/.
- Disaster Preparedness for Radiological Professionals. 2002. American College of Radiology. Washington DC. See http://www.arc.org/.

Example: Cesium 137 in the PEAC tool

Let's pull up Cesium 137 in the PEAC tool. Its chemical formula abbreviation is Cs 137. This is a man-made element which has been detected at nuclear power plants. Industrial uses include food irradiation, soil density testing, and radiography. The atomic number 137 means that the total number of protons plus neutrons is 137. The atomic weight is 136.907. Protons and neutrons do not have exactly the same mass so when the atomic weight is calculated, the number totals to 136.907 rather than an even 137.

Cesium 137 is radioactive. It emits a beta particle with maximum of 1.176 MeV (1.176 million electron volts per beta particle) kinetic energy. Accompanying this emission is 0.66164 MeV of gamma radiation. There is no alpha particle emission.

The activity of Cerium 137 is 86.6912 curies per gram. Radiation activity is usually measured in curies or microcuries [10^6 microcuries = 1 curie]. Activity is directly related to the number of disintegrations per unit time. One disintegration per second = 2.703×10^{-11} curies. [One disintegration per second = 2.703×10^{-5} microcuries]. Disintegration means that the cesium 137 has emitted a beta particle forming Barium 137. Barium 137 is stable and not radioactive.

The half-life of cesium 137 is 30.2 years. This means that after 30.2 years, half of the cesium 137 will have disintegrated forming barium 137. The half-life can be calculated directly knowing the activity and atomic weight.

MeV (million electron volts per particle or gamma emission) is a unit of energy. 1 MeV = 1.603×10^{-13} joules.

The relationship between MeV of energy and rem of radiation exposure is not easy to predict. Let us look at two cases, one in which the radioactive isotope is taken internally (by inhalation or ingestion) and the other case where the isotope is external to the body, but the person receives a radiation dose from the beta particles and gamma radiation.

- Radioactive isotope inhaled or ingested: The U.S. Nuclear Regulatory Commission has codified the maximum annual exposure to radiation workers and general public from inhalation and ingestion of radioactive isotopes. This is in Title 10 of the Code of Federal Regulations, Part 20 Appendix B and is repeated in the PEAC tool. The worker exposure limit listed in 10 CFR part 20 is based on 5 rem/year, and the general public exposure limit is based on 0.1 rem/year.

- Radioactive isotope external to human body: The degree of penetration of beta particles into the human body from the isotope depends on the distance the particle travels and its kinetic energy. A beta particle of 1.176 MeV kinetic energy can travel slightly over 1 meter in air or several centimeters in water (or several centimeters into human flesh). Clinically, beta particles produce a burn indistinguishable from a thermal burn. Gamma radiation on the other hand is much more penetrating and can produce symptoms like that listed in table 1. Neither gamma radiation nor beta particles from an external source leave residual radiation in the body.

From 10 CFR part 20, the annual limit on intake (ALI) of Cesium 137 into the body corresponding to a 5 rem dose is 200 microcuries per year. The ALI takes into account exposure to any daughter isotopes produced in the body (some radioactive isotopes have radioactive daughter species). From the ALI value, the derived air concentration (DAC) for inhalation is computed assuming a worker exposure of 2000 hours per year and a breathing rate of 20 liters per minute. The general public is based on a 0.1 rem annual exposure limit, 24 hours per day and 365 days per year. The drinking water limit is based on 730 liters intake per year.

- Annual Limit on Intake of Cesium 137 for 5 rem dose: 200 microcuries
- Max. Occupational Derived Air Concentration, 5 rem dose/year: 6×10^{-8} microcuries/ml
- Max Public Air Concentration, 0.1 rem dose/year: 2×10^{-9} microcuries/ml
- Max Public Water Concentration, 0.1 rem dose/year: 2×10^{-5} microcuries/ml.

If there is more than one radioactive isotope in the air or water, all isotopes must be considered as contributing to the radiation dose.

The external radiation exposure calculation is a little complicated. The dose depends upon whether the cesium 137 comes from a point source some distance away from the emergency responder, is uniformly distributed in the air (the responder is assumed to have an air pack), or is distributed as dust on the responder's protective suit. For example, let us calculate the radiation dose received by a person located one meter away from one gram of cesium 137. The first step is to calculate a flux (units: gamma photon radiation/sq. meter-second) at a distance one meter from the source. Then the flux is converted to a dose rate (units: rem/hour) using lookup tables that are located in the following reference source:

"Neutron and Gamma-Ray Flux-to-Dose Rate Factors", American National Standard, ANIS/ANS-6.11. 1977.

Other reference sources are available; this is not the only one. The flux itself is computed using a formula which has constants pulled from lookup tables. The calculations are too complicated to walk through and explain in this write-up but when we are done, the flux at one meter away is computed to be $2.6 \times (10)^{11}$ gamma photons/m^2-s, and the radiation dose rate is 38 rem/hour. A person one meter away might receive 114 rem dose after 3 hours. This is enough to manifest itself with clinical symptoms (nausea, may appear several days later), a decrease in blood lymphocytes (see table 1), and increased cancer risk later in life.

The gamma radiation flux (and the dose rate) falls off as the inverse square of the distance from the source. This means that if the 1-gram gamma radiation source were located 10 meters away, the dose rate would be only 0.4 rem/hour. On the other hand, if a person were dressed in a Level A protection suit and the suit becomes covered with cesium 137 dust, the dose rate can be very high. Additional Reading

- Medical Management of Radiological Casualties, 2nd edition, April 2003. Armed Forces Radiobiology Research Institute, Bethesda MD. A copy may be obtained from http://www.afrri.usuhs.mil/.
- Disaster Preparedness for Radiological Professionals. 2002. American College of Radiology. Washington DC. A copy can be obtained from http://www.arc.org/.