Basics Of Nuclear Radiation

Introduction

RAE Systems radiation monitors can be used to guard against and search for sources of various types of nuclear radiation. What are these types of radiation? Where do they come from? What levels are of concern? Can they contaminate a monitor? This Technical Note addresses such questions.

Four Common Types of Nuclear Radiation

There is radiation all around us – sunlight, radio waves, microwaves, infrared (heat), and even cosmic rays. These types of radiation consist mostly of electromagnetic waves, where the shorter the wavelength, the higher the energy of the photons. Most of these are harmless, either because their photon energy is too low or their intensity is too low.

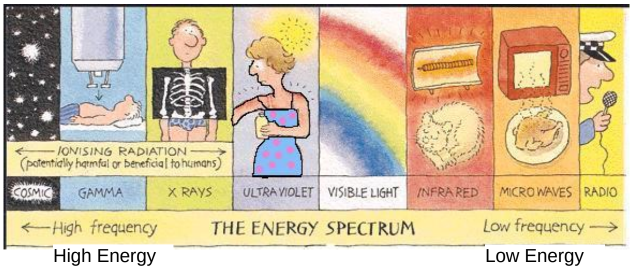

Figure 1. Electromagnetic Radiation Spectrum.

(From Brooke Buddemeier, Understanding Radiation and Its Effects, UCRL-PRES-149818-REV-2, Lawrence Livermore National Laboratory)

Nuclear radiation is different in that:

1. it consists of particles (alpha, beta, and neutrons) as well as short-wavelength waves (gamma).
2. Its energy is high enough to ionize molecules and thus cause biological damage.

Nuclear radiation is sometimes also called “ionizing radiation.” The biological damage caused by a radiation source depends on the dose received, which in turn depends on the source intensity and the extent to which that source is shielded. Being near radioactive material will not make you radioactive. However, neutrons can “activate” other atoms and create radioactive isotopes. All sources follow the inverse-square law for intensity: the dose received is four times less at double the distance from the source.

Alpha Particles (α)

Alpha particles consist of two neutrons and two protons. These relatively heavy particles with a 2+ charge are absorbed in a very thin layer of body tissue, piece of paper, or a few centimeters of air. Therefore, it is difficult to detect and direct exposure is unlikely. Alpha particles are hazardous only when inhaled, ingested, or injected. If an α-emitting source is inhaled, it can cause severe damage to the lungs and respiratory tract. Damage is localized because all the energy is deposited in a very thin layer. Alpha detectors require probes be placed very close to a source.

Beta Particles (β)

Beta particles are electrons or positrons, which have a single negative or positive charge, respectively, and weigh 1/1837th the amount of a proton. Beta particles can pass through a sheet of paper and some clothing, but are stopped by thin metal or glass. Beta particles can damage skin, but like alpha particles, the greatest hazard comes when a person inhales, ingests, or injects materials that emit beta (β) particles. Beta detectors also require probes that can be placed very close to a source.

Gamma Rays (γ) and X-rays

Gamma rays are a form of electromagnetic radiation similar to X-rays. The difference between them is in their origination: γ-rays originate from energy changes in the nucleus of an atom, while X-rays originate from the orbital electrons. They travel at the speed of light and penetrate most objects without much change in wavelength, but with gradual reduction in intensity. They pass through the air almost unaffected, but can be shielded using several feet of water, a few feet of concrete, several inches of steel, or a few inches of lead. Because it is not easily attenuated, γ-radiation is the most common means of both detection of, and human exposure to, radiation sources. Most radioactive sources emit some γ-rays, in addition to the α, β, or neutrons.

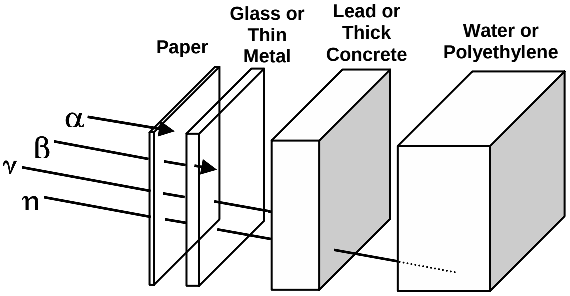

Figure 2. Radiation Shielding.

Neutrons (n)

Some heavy elements decay to others by ejecting neutrons from their nucleus during fission. The neutrons are emitted with high kinetic energy, which is gradually dissipated by collisions with molecules in the air or other media. The minimum energy is that of molecules diffusing through air at room temperature – these are called "thermal neutrons." Neutrons travel far through air and are stopped by a several feet of water or concrete. They are trapped more readily by lighter elements (e.g., hydrogen in water) than by the heavier ones like the lead used to stop γ-rays. Neutron radiation is not very common but poses an exposure risk if present because it is hard to shield. Neutrons are emitted by weapons-grade plutonium, and therefore neutron monitors are a means of detecting illicit nuclear weapons trafficking.

Radioactive Decay Process and Half-life

Radioactive decay results from elements with unstable nuclei emitting alpha, beta, or neutron particles and thereby converting to different elements. Gamma radiation is incidental to this process as a way to emit the excess energy released. Alpha emission removes two protons from the element,forming a new element two atomic numbers lower. For example:

$$^{239}\mathrm{Pu}_{94} \rightarrow {}^{235}\mathrm{U}_{92} + {}^{4}\alpha_{2} \qquad (+\gamma)$$

Beta emission converts a neutron into a proton, forming an element one atomic number higher:

$$^{137}\mathrm{Cs}_{55} \rightarrow {}^{137}\mathrm{Ba}_{56} + \beta^{-} \qquad (+\gamma)$$

Neutron emission does not necessarily change the element type, but is often associated with fission (splitting) of the parent element to two other elements:

$$^{240}\mathrm{Pu}_{94} \rightarrow {}^{137}\mathrm{Cs}_{55} + {}^{100}\mathrm{Y}_{39} + 3\eta$$

Decay of one radioactive element may result in the formation of another radioactive one, which decays further until a stable element is formed. Each step may release different types of radiation. For example:

$^{222}\mathrm{Rn}_{86}$ ($t_{1/2}$ = 3.8 days) → α +

$^{218}\mathrm{Po}_{84}$ (3.1 mins) → α +

$^{214}\mathrm{Pb}_{82}$ (27 mins) → β^{-} +

$^{214}\mathrm{Bi}_{83}$ (20 mins) → β^{-} + $^{214}\mathrm{Po}_{84}$ (164 µsec) → α + $^{210}\mathrm{Pb}_{82}$ (21 years) → β^{-} + …..

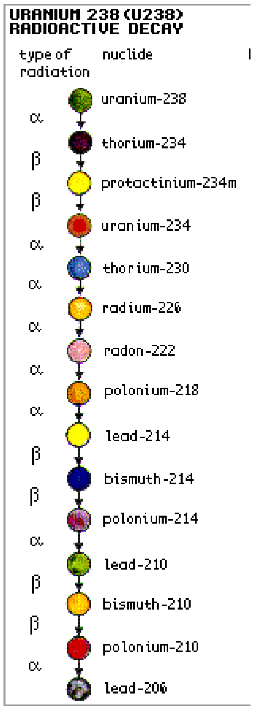

Figure 3. Radioactive Decay Chain leading from Uranium-238 to Radon-222 Gas and Ultimately to Stable Lead-206.
(From Brooke Buddemeier, Understanding Radiation and Its Effects, UCRL-PRES-149818-REV-2, Lawrence Livermore Nat. Lab.)

The time it takes for half of a given number of atoms to decay is called the *half-life.* Half-lives can range from microseconds to billions of years. Figure 4 illustrates the amount of radioactivity remaining after a given number of half-lives. For example, naturally occurring radon gas ($^{222}\mathrm{Rn}_{86}$) converts to lead ($^{210}\mathrm{Pb}_{82}$) with a half-life of 3.8 days. After two half-lives (7.6 days), one-quarter of the original radon and its radioactivity remain, and after 10 half-lives (38 days), only 0.1% of the original radioactivity remains and 99.9% of the radon has transformed to lead metal.

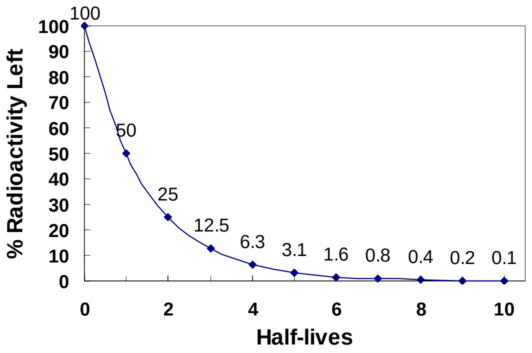

Figure 4. Radioactivity Decay Time Profile.

Elements with very short half-lives (<seconds) do not exist long enough to cause siginificant human exposure. Elements with very long half-lives persist for very long times with lower radioactive intensity.

Radiation Units & Nomenclature

Radiation units can be understood in three simplified steps:

1. The intensity of the radiation source (similar to the sun's intensity).
2. The amount (dose) of that intensity that is absorbed by a target detector or person (like the amount a sunbather's skin heats up).
3. The biological effect the absorbed dose causes (or biological equivalent dose, like the sunburn caused).

Table 1. Radiation Units and Equivalents.

Description	Unit	Equivalent
Intensity of a radioactive source material (dpm or disintegrations per minute)	becquerel (Bq)	2.7 x 10^{-11} Ci
	curie (Ci)	3.7 x 10^{10} Bq 2.2 x 10^{12} dpm
Dose absorbed by a target measured by **energy deposited** (1 rad = 100 ergs/g)	gray (Gy)	100 rad
	rad	0.01 Gy
Dose absorbed measured by its **chemical effect**	roentgen	~0.8-1 rad
Dose absorbed by a target measured by its **biological effect**	sievert (Sv)	100 rem
	rem (R)	0.01 Sv

Note: The unit roentgen is the quantity of radiation that forms 2.58 x 10^{-4} coulombs of ions per kg of air. The abbreviation "R" has historically been used for the roentgen, but it stands for *rems* on RAE Systems monitors.

Biological Effects

The difference between rads and rems (or grays and sieverts) is that various types of radiation cause different biological effects. Thus, the absorbed energy in rads is converted to a measure of biological equivalent dose (rems) using a quality factor, Q:

$$\text{rem} = \text{rad} \times Q_R$$
$$\text{sievert} = \text{gray} \times Q_G$$

where: $Q_R \equiv 1.0$ for 200 keV γ radiation
$Q_R \cong 1$ for tens to thousands keV γ radiation
$Q_R \cong 1$ for β particles
$Q_R \cong 20$ for α particles
$Q_R \cong 2$ to 20 for neutrons

Note that $Q_R \neq Q_G$. Q_R is the quality factor for rads to rems, and Q_G is the quality factor for grays to sieverts. The dose measured in rem (roentgen equivalent man) or sieverts (Sv) shows the biological effects, as indicated in Table 2. The effects increase with the dose, although there is a threshold of about 10 rem (100 mSv) below which no biological effects on humans are detectable.

The Q_R values listed above are for whole-body irradiation. More refined quality factors can be applied for specific organs and tissues, which differ in radiation sensitivity. The chemical form of the radioactive element further dictates the biological effects, because various elements accumulate in different parts of the body or to different extents.

Table 2. Biological Effects of Radiation.

Dose (Sv)	Dose (rem)	Effect of Acute, Whole-Body Dose
>4.0	>400	Death.
4.0	200 to 400	Severe radiation illness. Bone marrow and intestine damage, loss of red and white blood cell production, internal bleeding, vomiting, diarrhea. 50% of people die within 60 days @ 200 rem.
1 to 2	100 to 200	Mild radiation illness. Tiredness, vomiting, lack of appetite, temporary hair loss. Reduction in blood cell counts. Effects are reversible.
0.1 to 0.5	10 to 50	No feelings of illness, but blood samples may reveal temporary loss of white blood cell count.
<0.1	<10	No detectable effects on humans.

* **Note**: 1 rem = 1 million µrem or 1,000,000 µR
1 Sv = 1 million µSv or 1,000,000 µSv

Typical ambient exposure doses are well below those that can cause biological damage, as shown in Table 3.

Background Radiation Levels

Natural sources of radiation are present everywhere but normally are too low to be harmful (typically <20 µR/h). This radiation mostly comprises low-energy γ-rays from cosmic sources, local geological sources including radon and traces of uranium, local building materials, fertilizers, and global fallout from nuclear testing. Radon gas entering basements of homes is the main background human exposure in most regions. Even the human body naturally contains trace amounts of radioactive elements. Snow cover reduces the background from geologic sources, and high elevations increase the background from cosmic sources. Because the background levels can vary, it is frequently desirable to reset the background reference value on a monitor to correctly detect an illicit source moving into a location. The average person not working with radiaoctive materials typically absorbs a background dose of 0.1 to 0.2 rem/year (0.001 to 0.002 Sv/yr or 100,000 to 200,000 µR/yr).

Table 3. Typical Exposure Doses.

Dose (µSv)	Dose (µrem)	Source or Limit
3	300	Approximate daily background dose from natural sources.
30	3000	Approximate dose for a 10-hour plane flight.
100-200	10,000-20,000	Typical dose from a medical or dental X-ray.
700	70,000	Typical annual dose from medical X-rays and treatments.
1000-2000	100,000-200,000	Typical annual background dose from natural sources.
<1000-3000	<100,000-300,000	Typical annual dose from radon in homes.
1000-5000	100,000-500,000	Typical annual dose from all sources for the average person.
50,000	5 million (5 rem)	Maximum annual dose for a worker in a radiation-related industry.

Which is Worse: Short or Long Half-life?

Radiation hazard depends primarily on the intensity reaching the body. Materials with an intermediate half-life (months to hundreds of years) are the most hazardous because it is easier to achieve a high radiation intensity with a smaller amount of material. These materials have active decay processes but are stable enough to persist and cause long-term exposure. Materials with long half-lives, such as natural uranium ($t_{1/2}$ = 4.5 billion years) are less dangerous because they simply do not release much radiation per unit time. Short-life materials generate the highest short-term intensity, but can be rendered harmless simply by storing them under shielding until the radiation reaches background levels. Sometimes a radiation hazard is caused by radioactive material that has contaminated clothing, shoes, or skin and thereby inadvertently spreads to homes or other areas that are not monitored for radiation. In such cases, a long half-life causes greater concern.

Monitor Contamination

Nuclear radiation by itself does not contaminate a monitor or other surface it reaches. The radiation either passes through the monitor or is captured and converted to harmless forms of energy like heat. Exposure to radiation does not cause the monitor itself to become radioactive. The exception to this is neutron radiation. Neutrons can be captured in the nucleus of a stable atom and transform it into a radioactive isotope. To become contaminated, the monitor must come in contact with the radioactive material and collect some on its surface. In this case the monitor itself should warn of the presence of the contamination.

GammaRAE II & NeutronRAE II Instruments

GammaRAE II and NeutronRAE IIs are miniature radiation monitors that meet ITRAP (Illicit Trafficking of Radiation Assessment Program) requirements for the detection of illegal radioactive materials (see Technical Note TN-177 for details on ITRAP). The GammaRAE II measures gamma rays and the NeutronRAE II measures both gamma and neutron radiation. Neither unit significantly detects alpha or beta particles. Special equipment is needed to detect these particles, although alpha and beta emitters usually also emit some gamma. The GammaRAE II and NeutronRAE II are not intended for use as personal dosimeters because they are not compensated for the energy of the radiation and they can have a slight RF interference.

Response and Alarm Times

The GammaRAE II and NeutronRAE IIs update the display every 0.25 seconds. The displayed value is the average of the previous 8 measurements over 2.0 seconds. Therefore, the signal may take a few seconds to increase to a stable reading when exposed to a radiation source, or to decrease to the background level when removed from the source.

The alarm time depends on the threshold setting (n factor) and the intensity of the source. For example, if the n value is set to alarm at 10% above background readings, then the alarm begins 2 seconds after exposure to 8 consecutive readings that are barely 10% above background, 1 second after 2 readings at 40% above background, or after 0.25 seconds if the intensity is ≥80% over the background.

How are RAE Systems Monitors Factory Calibrated?

The GammaRAE II and NeutronRAE II monitors are calibrated using a collimated ^{137}Cs gamma source. The distance from the source is varied to give a dose equivalent rate (DER) of exposure at the extremes of the DER range given in the instrument specifications. For example, for the GammaRAE II the maximum error allowable is 30% at the extremes of 10 and 4000 μR/h.

How Do I Calibrate or Test the Monitor?

GammaRAE and NeutronRAE II monitors do not need user calibration under normal circumstances. They should remain within the specifications for the life of the instrument (some companies require that the units be sent to a test laboratory at regular intervals).

The function of the monitor should be obvious from the display because there always exists a background signal. If a more rigorous function or alarm test is desired, various low-level radiation sources can be used, such as a smoke alarm with a ^{241}Am sensor, a low-level ^{137}Cs source available from a laboratory supply house, or even some ceramics, rocks (granite), or potassium-containing fertilizers.

Setting the Alarm Level

Unlike chemical exposure monitors, radiation monitor alarm levels are not set to a fixed alarm setpoint. This is because the alarm level usually must be close to the background radiation level to maximize the sensitivity for detecting sources. Because the background changes with location and time and is frequently reset by the user, the alarm level is automatically reset whenever the background is remeasured. Thus, the alarm level is set to a percentage above the background value rather than to a fixed point.

$$\text{Alarm Setpoint} = N + n\sqrt{N}$$

where:

N is the background reading during reference calibration.
n is the alarm sensitivity set by the user.

According to this formula, the percentage above background varies with the actual background level and the n value set by the user.

Table 4. Alarm point vs background and n value.

n	N (Background cps)	Alarm Point (cps)	% Above Background
1	100	110	10
1	200	214	7
1	1000	1032	3
5	100	150	50
5	200	271	35
5	1000	1158	16

What Does the % Number Under the Main Display in the GammaRAE II Mean?

The % display on the GammaRAE II is a measure of the deviation of the response. The number is high whenever the readings are changing, and low when the readings are stable. For example, the % deviation is high if the source (including the background) is fluctuating, or when the monitor has been moved to or from a source. The % readings are not needed for searching, but can be useful to detect if a source is moving or changing rapidly.

Radon in Homes

Radon gas in home basements is one of the major background radiation sources, particularly in the Northeast and Rocky Mountain regions of the US. It can usually be reduced to below significant levels by increasing the ventilation of the basement. Although the GammaRAE II and NeutronRAE II may measure high concentrations of Radon, other instruments such as the RadonRAE or RadonRAE Progeny are more suitable for this.

Medical X-Ray Detection

X-rays used in medicine can be pulsed or continuous and have energies typically from 0.01 to 0.25 MeV. Since the GammaRAE and NeutronRAE IIs have lower energy limits of 0.03 MeV, most, but not all, of the X-rays can be detected. Continuous and moderate pulses can be detected, but very short pulses may not be detected even within the energy range.

Common Radioactive Nuclides

Table 5 below lists some radioactive elements and their common sources. Note that the major decay mode indicates only the first step. Subsequent steps may emit other particles, and most steps emit gamma rays in addition to the particles.

Table 5. Some Common Radioactive Sources

Radio-Nuclide	Major Decay Mode	t½	Common Sources & Uses
^{241}Am Americium	α	458 y	Smoke detectors
^{239}Pu Plutonium	α	24360 y	Weapons-grade plutonium
^{238}U Uranium	α	4.5 billion y	Most abundant (99.3%) natural uranium isotope. Half-life of 4.5 billion years.
^{235}U Uranium	α	713 million y	0.7% of natural uranium. Enriched up to 95% for weapons, 5% for commercial power reactors.
^{222}Rn Radon	α	3.82 d	Naturally occuring in ground from uranium decay. Home radiation source.
^{137}Cs Cesium	β	30 y	Major radiation source in spent nuclear fuel. Medical treatment; industrial radiography
^{90}Sr Strontium	β	29 y	Major radiation source in spent nuclear fuel and fallout from nuclear bombs
^{14}C Carbon	β	5730 y	Present in all living organisms and used to measure age of dead organisms
^{40}K Potassium	β	1.9 million y	Potassium-enriched fertilizers; present in human body, bananas
^{3}H Hydrogen	β	12 y	Used in scientific and medical tracer studies; night-vision instruments
^{131}I Iodine	β	8.1 d	Radiopharmaceutical used to treat excessive thyroid hormone production
^{60}Co Cobalt	β & γ	5.3 y	Medical X-ray machines and food sterilization
^{252}Cf Californium	α*	2.6 y	Medical and research use; mining and oil exploration
^{240}Pu Plutonium	α*	6570 y	Minor isotope in weapons-grade plutonium; more prevalent in unrefined plutonium
^{99m}Tc Technitium	γ	6 h	Medical imaging (γ only; internal transition)

* Note that ^{252}Cf and ^{240}Pu both also decay by spontaneous fission, which releases neutrons. However, fissions only account for 1/31 of the decays in ^{252}Cf, and less than 0.001% of the decays in ^{240}Pu.

Neutron Detection

Although NeutronRAE II monitors can detect neutrons in the energy range thermal – 14 MeV, they are most sensitive to the lower-energy radiation. Table 6 gives examples of the neutron energy of some sources. For example, the NeutronRAE II is 5 times more sensitive to ^{252}Cf than to an Americium/ Beryllium neutron generator because ^{252}Cf's neutrons are much slower. Moreover, the sensitivity can be increased by moderators that slow the neutrons, such as water, wax, or graphite (as long as they don't completely absorb the neutrons). Wearing a NeutronRAE II on a belt increases its sensitivity by up to a factor of 5 by virtue of the human body slowing the neutrons. If the source is placed inside a moderator shielding, the sensitivity can be increased by another factor of 5. Thus, the presence of moderators greatly affects the ability of the NeutronRAE II to detect a neutron source.

In addition to Cf having slower neutrons, it generates far more neutrons per curie than an Am/Be or Pu/Be generator. Thus, Cf is far more responsive per curie than Am/Be or Pu/Be, both because it generates more neutrons and because each neutron is slower.

Table 6. Some Common Neutron Sources.

Neutron Source	Neutron Energy (MeV)	Relative Response per neutron	Neutron Output (η/sec/Ci)
^{241}Am/Be	5.0	1	(2-3) x 10^6
^{239}Pu/Be	4.5	1.2	(3-4) x 10^6
^{252}Cf	2.14	5	4.4 x 10^9

Weapons-grade plutonium is relatively pure, and typically consists of about 94% ^{239}Pu and 6% ^{240}Pu, whereas "dirty" plutonium contains up to 30% ^{240}Pu plus other isotopes. Because ^{240}Pu emits neutrons and ^{239}Pu does not, it is easier to detect "dirty" plutonium using a NeutronRAE II.

Note: Do not confuse "dirty" plutonium, a potential precursor to a nuclear explosive device, with a "dirty bomb," which is considered to be a conventional explosive laced with any radioactive material as a means of spreading the radioactivity.