BASICS OF NUCLEAR RADIATION

Introduction

RAE 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 my monitor? This Technical Note clarifies such questions.

Four Common Types of Nuclear Radiation

There is radiation all around us – sunlight, radio waves, microwaves, infrared (heat), even cosmic rays. This type of radiation consists 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.

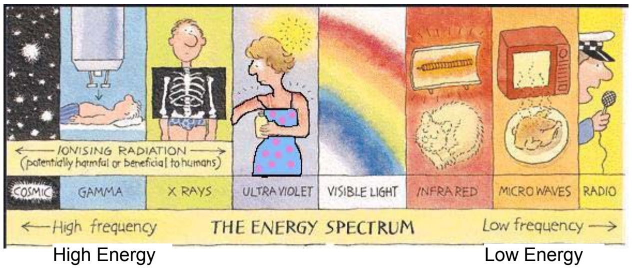

Figure 1. Electromagnetic Radiation Spectrum

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 & 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. In general the more penetrating radiation (gamma & neutron) causes less damage but is harder to shield, whereas the least penetrating radiation (alpha & beta) is the most damaging but can be more easily shielded. All sources follow the inverse-square law for intensity: the dose received is 4 times less at double the distance from the source.

Alpha Particles (α)

Alpha particles consist of two neutrons and two protons. This relatively heavy particle is absorbed in a very thin layer of body tissue or piece of paper or a few cm of air. Therefore, it is difficult to detect and direct exposure is unlikely. Alpha particles are hazardous only when inhaled, ingested, absorbed, 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 charge 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 absorbs materials that emit β particles. Beta detectors also require probes that can be placed very close to a possible source.

Gamma Rays (γ) and X-rays

Gamma rays are a form of electromagnetic radiation similar to X-rays. 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 they are 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. X-rays have about equal or lower energy than γ-rays.

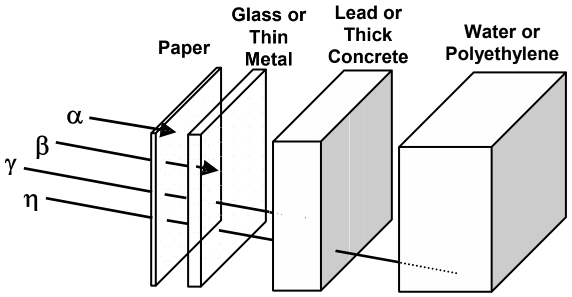

Figure 2. Radiation Shielding

Neutrons (η)

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 collision 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 few 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-type plutonium and therefore neutron monitors are a means of detecting illicit nuclear weapons trafficking.

Radiactive 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:

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

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

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

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

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

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:

$^{222}\text{Rn}_{86}$ ($t_{1/2}$ = 3.8 days) → α +
$^{218}\text{Po}_{84}$ (3.1 mins) → α +
$^{214}\text{Pb}_{82}$ (27 mins) → β +
$^{214}\text{Bi}_{83}$ (20 mins) → β +
$^{214}\text{Po}_{84}$ (164 μsec) → α +
$^{210}\text{Pb}_{82}$ (21 years) → β + …..

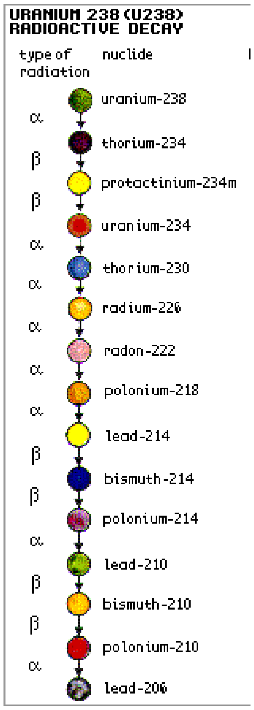

Figure 3. Radioactive Decay Chain leading from Uranium-238 to Radon-222 Gas and Ultimately to Stable Lead-206

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 ($^{222}\text{Ra}_{86}$) converts to lead ($^{210}\text{Pb}_{82}$) with a half-life of 3.8 days (see above). After two half-lives (7.6 days), one-quarter of the original radon and its radioactivity are remaining, and after 10 half-lives (38 days), only 0.1% of the original radioactivity is remaining and 99.9% of the radon has transformed to lead metal.

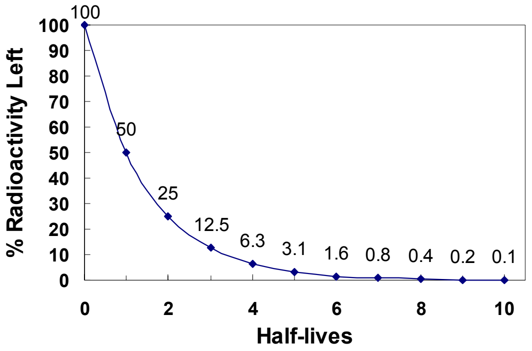

Figure 4. Radioiactivity Decay Time Profile

Elements with very short half-lives (<seconds) do not exist for 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 intensitiy 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. This unit is no longer used in the international system, where the preferred unit is grays. The abbreviation "R" has historically been used for the Roentgen, but it stands for rems on RAE 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 hazard (rems) using a quality factor Q:

$$\text{rem} = \text{rad} \times Q$$
$$\text{sievert} = \text{gray} \times Q$$

where:
$Q \equiv 1.0$ for 200 keV γ radiation
$Q \cong 1$ for 10’s to 1000’s keV γ radiation
$Q \cong 1$ for β particles
$Q \cong 20$ for α particles
$Q \cong 2 - 20$ for neutrons

The dose measured in rem (radiation equivalent man) or Sieverts (Sv) controls the biological effects, as shown 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 values listed above are for whole body irradiation. More refined quality factors can be applied for specific organs and tissues, which often differ in sensitivity. The chemical form of the radioactive element further modifies the biological effects, because various forms accumulate in different parts of the body or to different extents.

Table 2. Biological Effects of Radiation

Dose (µSv)	Dose (µrem)	Effect of Short-Term, Whole-Body Dose
>3.5 million	>350 million	Death
2.0-3.5 million	200-350 million	Severe radiation illness. Bone marrow and intestine damage, loss of red and white blood cell production, internal bleeding, vomiting, diarrhea.
1-2 million	100-200 million	Mild radiation illness. Tiredness, vomiting, lack of appetite, temporary hair loss. Reduction in blood cell counts. Effects are reversible.
0.1-1 million	10-100 million	No feelings of illness, but blood samples may reveal temporary loss of white blood cell count.
<0.1 million	<10 million	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 is mostly comprised of 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 some 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 0.1-0.2 rem/year (0.001-0.002 Sv/yr or 100,000-200,000 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	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 a short half-life can be considered more hazardous because it is easier to achieve a high radiation intensity with a smaller amount of material. On the other hand, at a given intensity, the material with a longer half-life is considered more dangerous because it will persist for many years. Short-life materials can be rendered harmless simply by storing them under shielding until the radiation reaches background levels. Sometimes a radiation hazard is caused by contacting the radioactive material on clothing, shoes or skin and thereby inadvertently spreading it 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 will 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 to become radioactive itself. 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 & NeutronRAE Instruments

GammaRAE and NeutronRAE Pagers are miniature radiation monitors that meet ITRAP (Illicit Trafficking of Radiation Assessment Program) requirements for the detection of illegal radioactive materials (See Technical Note 177 for details on ITRAP). The GammaRAE measures gamma rays and the NeutronRAE measures both gamma and neutron radiation. Neither unit detects alpha or beta rays. Special equipment is needed to detect these rays, although alpha and beta emitters usually also emit some gamma. The GammaRAE and NeutronRAE 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 and NeutronRAE Pagers 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 background 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 Monitors Factory Calibrated?

The GammaRAE and NeutronRAE 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 Pager 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 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, 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 cal
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 mean?

The % display on the GammaRAE is a measure of the deviation of the response. The number will be 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.

Medical X-Ray Detection

X-rays used in medicine can be pulsed or continuous and have gamma energies typically from 0.01 - 0.25 MeV. Since the GammaRAE and NeutronRAE Pagers 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-type plutonium
^{238}U Uranium	α	4.5 billion y	Most abundant (99.3%) natural uranium isotope. Half-life 4.5 billion years.
^{235}U Uranium	α	713 million y	0.7% of natural uranium. Used to enrich uranium for nuclear reactors & weapons
^{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	28 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
^{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	5.3 y	Medical X-ray machines and food sterilization
^{252}Cf Californium	η	2.6 y	Medical and research use; mining and oil exploration
^{240}Pu Plutonium	η	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)

Neutron Detection

Although NeutronRAE 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, Californium (^{252}Cf) is about 5 times more sensitive per neutron than an Americium/Berrylium source because of its slower neutrons. 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 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 tha ability of the NeutronRAE to detect a neutron source.

In addition to Cf having inherently sensitive (slower) neutrons, it generates far more neutrons per curie than an Am/Be or Pu/Be source. 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 more sensitive.

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
^{240}Pu			
^{244}Cm			

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.

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.