Competency 2.1 **Personnel shall demonstrate knowledge of radiological controls, practices, procedures, and theory.**

1. SUPPORTING KNOWLEDGE AND SKILLS

a. Define "ionizing radiation."

b. Describe how nuclear radiation is generated.

c. Describe each of the following forms of radiation in terms of structure, electrostatic charge, interactions with matter, and penetration potential:
   - alpha
   - beta
   - gamma
   - neutron (slow and fast)

d. Discuss the types of materials that are best suited for shielding the above radiation types.

e. Describe the biological effects and the primary hazard(s) of each radiation type.

f. Discuss radiation dose and how it is measured, including the terms "rad," "rem," "roentgen," and "international standard units (SI)."

g. Define "Quality Factor" and describe how it is used.

h. Define the term ALARA and describe the basic methods for achieving ALARA.

2. SUMMARY

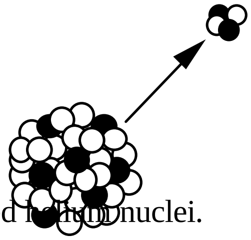
A variety of radiations are frequently encountered at DOE facilities. These radiations can be classified into two broad categories--ionizing and nonionizing. **Ionizing** radiations are those radiations that possess sufficient energy to eject electrons from neutral atoms. They include alpha particles, beta particles, gamma rays, x-rays, and neutrons. **Nonionizing** radiations can excite electrons to higher energy states, but do not possess sufficient energy to eject electrons from the atom. Examples of nonionizing radiations (or devices that produce nonionizing radiations) include ultraviolet, visible, infrared, microwave and radio, power frequencies, radar, and lasers.

Both ionizing and nonionizing radiations pose potential health hazards in the workplace. Radiological controls and practices should be tailored to the facility and the specific radiation hazard(s). The focus in this competency is to emphasize **ionizing radiations**.

Ionizing radiations can be generated via natural or man-made processes. Natural sources of radiation and radioactivity include cosmic radiations, cosmogenic radionuclides (those radionuclides produced by comic ray bombardment with the upper atmosphere), terrestrial radiations, radionuclides in the body, and radon. Man-made sources include medical diagnosis and therapy, consumer products, occupational activities, miscellaneous environmental activities (for example, air emissions from DOE facilities), and exposures associated with nuclear power generation.

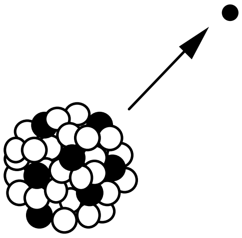
The figures below depicts the most commonly encountered ionizing radiations. Note that with the exception of x-rays, each of the radiations is emitted from the nucleus of the atom. X-rays are produced by electronic transitions between shells that surround the nucleus.

Alpha Particles



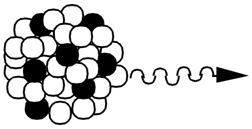
- Positively charged helium nuclei.
- Particulate radiations with relatively high energies, but weak penetrating abilities.
- Unlike other ionizing radiations, do not constitute an external hazard.

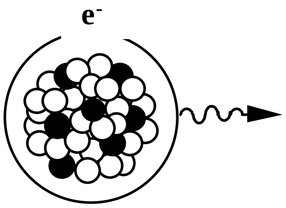
Beta Particles



- High-speed electrons formed by the conversion in the nucleus of a neutron into a proton or a proton into a neutron.
- Can be either negatively charged (negatron) or positively charged (positron).
- Particulate radiations with a range in matter greater than an alpha particle.

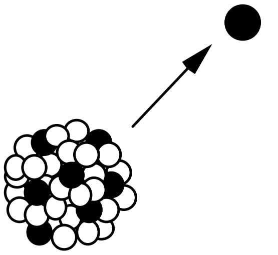
Gamma Rays and X-rays





- Electromagnetic radiations with no charge or mass.
- Distinction between gamma rays and x-rays based on origin and energy: gamma rays produced within the nucleus; x-rays outside the nucleus. X-rays, in general, have lower kinetic energies (lower EM frequencies) than gamma rays.
- Very penetrating forms of radiation that travel indefinite distances.

Neutrons



- Particulate radiations with no charge.
- Wide range of energies ranging from thermal (0.025 eV) to fast (several MeV).
- Very penetrating forms of radiation that travel indefinite distances.

Several characteristics of these ionizing radiations are noted in the table below.

Characteristics of Ionizing Radiation

Type	Symbol	Compo-sition	Mass (amu)	Charge	Typical Energies	Range (Air)	Range (Tissue)	Primary Hazard	Examples
Alpha Particle	α	2p + 2n	4	+2	4 - 8 MeV	few centimeters	50 to 70 micrometers	internal	uranium, radon, plutonium
Beta Particle	β	electron	0.00055	±1	.018 - 3 MeV	up to a few meters	few millimeters	external and internal	strontium-90, carbon-14, tritium
Gamma Ray	γ	electro-magnetic ray	0	0	0.1 - 2 MeV	indefinite	indefinite	external and internal	cobalt -60, cesium-137
X-ray	x	electro-magnetic ray	0	0	.01 - 150 keV	indefinite	indefinite	external and internal	x-ray machines
Neutron	n	neutron	1	0	0.025 eV - 15 MeV	indefinite	indefinite	external and internal	reactors, neutron sources

Some general points can be made for each of the radiations noted in the table.

Ionizing radiations constitute both internal and external hazards. For potential internal radiation hazards, the primary objective is to avoid taking in any radioactive materials into the body. This can be realized to a large extent by utilizing **containment** and **confinement techniques** along with cleanliness to minimize the risk of intake through inhalation, ingestion, injection, or open wounds. Adequate protection against excessive exposures to external sources of radiation can be provided by employing three major exposure-reducing principles: **time**, **distance**, and **shielding**. The control of exposure **time** (time spent in a radiation field) is the first major health physics principle available to an occupational worker to limit his/her exposure to an external radiation source. It is important to realize that the radiation dose received by the worker is **directly** proportional to the time spent in a radiation field. Therefore, to minimize the dose received, the time spent in the radiation field must be accordingly reduced. The control of exposure time is a significant factor in the issuance of radiation work permits (RWPs) common at DOE facilities.

A very common and extremely effective technique to reduce personnel exposure is to increase the **distance** between the worker and the radiation source. In many instances, this approach is more important than controlling exposure time and can be easily demonstrated for "point" (small) sources of radiation. While the exposure-time relationship follows a direct dependence, i.e., reducing the time spent in a radiation field by one-half reduces the exposure to the worker by one-half, distance dependence often follows the "inverse-square" (second power) law. Thus, doubling the distance from a point source reduces the exposure to the worker by a factor of four! It should be noted that situations do exist where the inverse square law does not apply. In these cases, the relationship between the dose received and the distance from the source does not always follow a simple rule.

A third factor for controlling external exposures entails the use of **shielding**. Shielding the source of radiation becomes important when minimizing time and maximizing distance are not sufficient to reduce personnel exposures to acceptable levels. Determining the required shielding is influenced strongly by the type (alpha, beta, gamma, x-ray, neutron) and energy of the radiation.

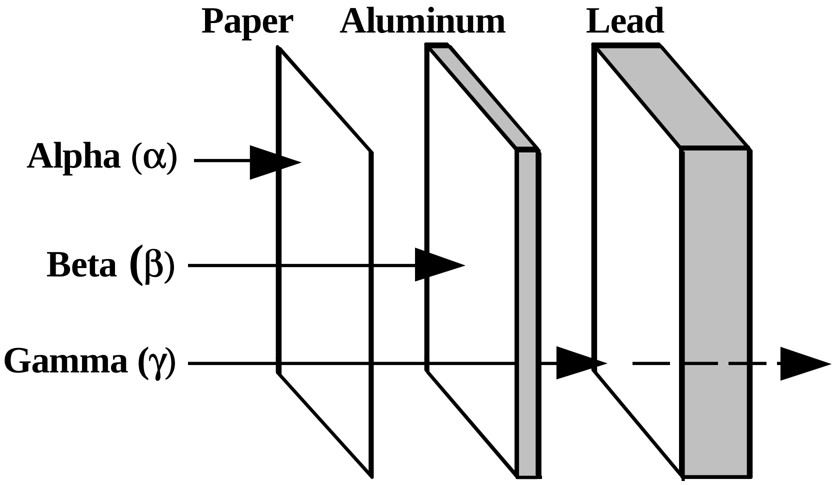
Alpha particles have typical energies on the order of 4 to 8 MeV, but rapidly lose this energy through the ionization process. This results in a short range (penetration) in air and tissue and minimal shielding requirements. Unlike alpha particles, beta particles are not emitted with discrete energies but follow a continuous energy distribution. In other words, beta particles are emitted from a particular radionuclide with energies ranging from zero to some maximum value. The maximum energy for a specific beta emitter is typically cited; this value can be found in various places in the literature and is characteristic of the radionuclide. Beta particles lose energy in a number of ways as they pass through matter: ionization and excitation are the most frequent mechanisms. Because of their light mass (the mass of an electron), beta particles do not nearly ionize to the same degree as alpha radiation. For example, for every centimeter of matter traversed, only about 45 electrons are ejected by a beta particle through the ionization process.

The fraction of energy emitted as bremsstrahlung through beta interactions with atomic nuclei is directly related (proportional) to the atomic number of the shielding material and the energy of the beta particle. Therefore, higher beta energies combined with higher atomic-numbered materials increases the occurrence and intensity of bremsstrahlung radiation. The fact that a charged-particle radiation can initiate the emission of penetrating bremsstrahlung (x-ray) radiation requires consideration of appropriate shielding. Beta sources should be shielded first with a low Z material (such as plastic) followed by a high Z material (such as lead). In this way, any penetrating radiation produced by beta interactions in the shield can be attenuated to a large degree by the higher density material. Otherwise, individuals working with and around beta sources could be exposed unnecessarily to photon radiation. However, given the energy of an alpha or beta particle, the range in any medium can be calculated and the appropriate amount of shielding determined.

Because they are uncharged, gamma, x-ray, and neutron radiations are more difficult to shield. The basic approach to gamma and x-ray shielding is to determine what the exposure rate is, and then, what it should preferably be after shielding. Calculations of the estimated amount of shielding of a particular material required to reduce the intensity of a beam of gamma or x-ray radiation are then performed. Neutron shielding is based on moderating (slowing down) and thermalizing high energy neutrons, often followed by capture processes. A wide range of shielding materials are used for these purposes. The following table identifies typical shielding materials for ionizing radiations.

Radiation Type	Shielding Materials
Alpha	Air, paper, dead layer of human tissue
Beta	Plastic, glass, aluminum
Gamma, x-ray	Lead, tungsten, iron, depleted uranium (in general, materials with high atomic numbers)
Neutron	Paraffin, polyethylene, water, boron, cadmium (in general, materials with low atomic numbers)

The following graphic shows the relative penetrating abilities of alpha, beta, and gamma radiations



Each of the radiations described thus far has the potential to cause a number of biological effects. These effects can be classified into stochastic and nonstochastic (deterministic) effects.

Stochastic effects

- Statistical in nature.
- Probability of the effect occurring within a population increases with dose.
- Generally assumed to have no threshold, implying that even low radiation doses cannot be excluded.
- Include cancer induction and genetic mutations.

Nonstochastic (Deterministic) Effects

- Severity in an individual varies with the magnitude of the radiation dose.
- The greater the dose, the more severe the effect.
- Assumed to have a threshold radiation value below which the effect is not observed.
- Examples include acute radiation effects observed in individuals exposed to large amounts of radiation, and opacity in the lens of the eye.

The effects of radiation upon biological systems depend primarily upon the total radiation dose and also upon the dose rate (how fast the dose is received). **Acute effects** (early effects) refer to biological effects that occur within one to two months following a radiation dose of approximately 10 rad or more. Inherent in the definition of an acute dose is that the dose was received acutely or promptly (i.e., over a period of up to a few hours). **Chronic** (delayed) effects, as opposed to acute effects, typically occur more than two months, and up to several years, after receiving much smaller doses accumulated steadily on a day-to-day, year-to-year basis.

Ionizing radiation is known to cause biological damage on the cellular level. Radiation is believed to interact primarily with the DNA molecule (deoxyribonucleic acid)--the carrier of genetic information. Radiation produces chemical changes that can eventually lead to cell death or other harmful effects. At low doses and low dose rates, biological repair mechanisms do exist to help counter a radiation "insult;" however, changes occurring on the cellular level can still translate into **carcinogenesis** (cancer induction), **mutagenesis** (genetic defects), and **cell lethality**.

Protecting occupational workers and the public from an elevated cancer risk is the main concern of regulatory agencies. Cancer induction is a stochastic effect that can be observed at low dose rates and over extended periods of time following exposure. Typical environmental levels are well below the threshold values for nonstochastic effects.

Because cancer induction is a stochastic effect, it is assumed to follow a no-threshold relationship with dose. Scientifically, however, this is very difficult to prove and is often debated by health effects experts. Nonetheless, the DOE assumes for regulatory purposes that there is no threshold for the onset of carcinogenesis.

There are several commonly encountered radiation quantities and units used in the field of radiation protection. The following table serves as a selected summary.

Quantity	Symbol	Units	Radiation Type	Absorbing Medium
Exposure	X	roentgen (R) coulomb/kilogram (C/kg)	gamma, x-rays	air
Absorbed Dose	D	rad gray (Gy) joules/kilogram (J/kg) ergs/gram	any ionizing radiation	any type
Dose Equivalent	H	rem sievert(Sv) joules/kilogram (J/kg) ergs/gram	any ionizing radiation	human tissue (living)

Additional information regarding these quantities and units includes:

Exposure (X)

- Basic concept - Describes an x-ray or gamma ray radiation field. It is a measure of the amount of ionization produced in air by x-rays or gamma rays.
- The conventional unit is the roentgen (R). In the international system (SI) of units, the coulomb/kilogram (C/kg) is substituted for the roentgen. One roentgen = 2.58×10^{-4} C/kg.
- The quantity exposure is only defined in air. It would be incorrect to say, "my dose was one roentgen" because the use of the roentgen indicates that reference is being made to the quantity exposure - a quantity not defined for human tissue.
- This quantity is considered outmoded by the International Commission on Radiation Units and Measurements (ICRU).

Absorbed Dose (D)

- Basic concept - Amount of energy absorbed per unit mass in the medium of interest.
- The conventional and SI units are the rad (no abbreviation) and the gray (Gy), respectively.
- Unit conversions: 1 Gy = 100 rad

1 Gy = 1 joule/kilogram (J/kg)

1 rad = 100 ergs/gram

- The quantity is not limited to photon radiations; it applies to all types of ionizing radiation.
- The quantity is not restricted to air, but is applicable to all types of material (air, water, human tissue, etc.).

Dose Equivalent (H)

- Basic concept - Has no precise or exact meaning. It is an administrative concept used for the purposes of radiation protection and is subject to change. It is only meant to apply at those doses commonly encountered in the field of radiation protection (in other words, it does not apply to large acute doses and accident situations). It is related to the amount of biological damage to a person from a given dose of radiation.
- The conventional unit is the rem (no abbreviation); the SI unit is the sievert (Sv).
- Unit conversions: 1 Sv = 100 rem
  1 Sv = 1 J/kg
- The quantity applies to all types of ionizing radiation.
- The quantity only applies to living humans.
- The dose equivalent (H) is the product of the absorbed dose (D) and the quality factor (Q); therefore, $H = D \times Q$.

Quality Factor (Q)

The quality factor (Q) relates the absorbed dose received by a worker to the dose equivalent. It only applies to chronic, low-level doses. Consider two individuals who receive the same absorbed dose (one worker from gamma rays, the other from neutrons). The biological damage (or risk) will be greater from the neutron dose. Regulatory controls are put in place to limit the risk, and some means must be used to take into account the different risks associated with different types of radiation. The quality factor is used for this purpose. Each type of radiation is assigned a quality factor based upon its potential to cause biological damage. The absorbed dose can then be multiplied by Q to calculate the dose equivalent. Typical quality factors for various radiation types are shown in the following table.

Radiation Type	Quality Factor
Gamma	1
X-ray	1
Beta	1
Neutrons $\leq$ 10 keV	3
Neutrons > 10 keV	10
Alpha	20

To minimize exposures to personnel from sources of ionizing radiation and any corresponding health effects, the Department of Energy places a strong emphasis on the concept of ALARA--an acronym standing for As Low As Reasonably Achievable. The ALARA philosophy is the cornerstone in a radiation protection program (RPP) for avoiding unnecessary doses and achieving the lowest radiation exposures to occupational workers and the general public as possible, taking into account economic, technological, and societal factors.

ALARA can be achieved in a variety of ways. Where internal doses are possible, good work practices should be encouraged and followed. These include:

- Refraining from eating, drinking, chewing, and smoking around radioactive materials.
- Wearing protective clothing.
- Performing adequate radiation monitoring before leaving an area.
- Washing hands before taking breaks or leaving the work site.

The above practices and others can go a long way towards reducing the inhalation or ingestion of radioactive materials into the body. For external radiation hazards, the previously mentioned radiation safety tenets of time, distance, and shielding are major exposure-reducing controls. Administrative controls, such as the use of radiation work permits and allowable job dose levels, are an essential ingredient in an ALARA program.

3. SELF-STUDY SCENARIOS/ACTIVITIES AND SOLUTIONS

Activity 1

Place the letter of the correct word next to the corresponding definition.

a. nonstochastic effect
b. quality factor
c. gray
d. rem
e. cancer induction
f. alpha radiation
g. shielding
h. neutron
i. x-rays
j. carrier of genetic code
k. roentgen
l. photon radiations
m. positron
n. natural radioactivity
o. ALARA

1. stochastic effects ________
2. applies only to photon radiations in air ________
3. exposure reducing method ________
4. SI unit for absorbed dose ________
5. example of a beta particle ________
6. as low as reasonably achievable ________
7. originate outside the nucleus ________
8. gamma rays, x-rays ________
9. cataractogenesis ________
10. measure of the biological effectiveness of the radiation ________
11. radon gas ________
12. weakly penetrating radiation ________
13. conventional unit for dose equivalent ________
14. deoxyribonucleic acid ________
15. particulate radiation with a neutral charge ________

Activity 1, Solution

1.	stochastic effects	e. cancer induction
2.	applies only to photon radiations in air	k. roentgen
3.	exposure reducing method	g. shielding
4.	SI unit for absorbed dose	c. gray
5.	example of a beta particle	m. positron
6.	as low as reasonably achievable	o. ALARA
7.	originate outside the nucleus	i. x-rays
8.	gamma rays, x-rays	l. photon radiations
9.	cataractogenesis	a. nonstochastic effect
10.	measure of the biological effectiveness of the radiation	b. quality factor
11.	radon gas	n. natural radioactivity
12.	weakly penetrating radiation	f. alpha radiation
13.	conventional unit for dose equivalent	d. rem
14.	deoxyribonucleic acid	j. carrier of genetic code
15.	particulate radiation with a neutral charge	h. neutron

Activity 2

A radiological control technician (RCT) takes a calibrated radiation survey instrument into a room containing gamma-emitting radioactive materials and notes that the reading on the instrument is 40 mrem/hr (millirem per hour). How long can this worker stay in the room without exceeding a predetermined total dose equivalent of 100 mrem?

Your Solution:

Activity 2, Solution

Since the exposure the RCT will receive is directly related to the time spent in the radiation field, dividing the exposure by the exposure rate will provide a time estimate, which in this case, should not be exceeded.

Equationally, $t = 100 \text{ mrem} \div 40 \text{ mrem/hr} =$ **2.5 hours**

Activity 3

The range of an alpha particle in air can be determined using the following empirical equation:

$$Range = 1.24E - 2.62$$

where:
R = the range in centimeters
E = the energy in MeV

a) Given a 6 MeV alpha particle, calculate its range in air.

b) Evaluate whether your answer is reasonable.

***Your Solution*:**

Activity 3, Solution

(Any reasonable paraphrase of the following is acceptable.)

a) Range (cm) = 1.24 (6) - 2.62 = **4.82 centimeters**

b) The range of this alpha particle is less than two inches in air. This answer is reasonable considering the fact that alpha particles lose their energy quickly through the ionization process. This calculation verifies that alpha particles do not have an extensive range in air (and therefore less in human tissue which has a higher density). It also illustrates how weakly penetrating these radiations are and how easily these particles can be shielded.

4. SUGGESTED ADDITIONAL READINGS AND/OR COURSES

Readings

- Argonne National Laboratory. (1988), *Department of Energy Operational Health Physics Training* (ANL-88-26). Argonne, IL.
- Gollnick, Daniel A. (1991. *Basic Radiation Protection Technology* (2nd ed.). Pacific Radiation Corporation: Altadena, CA.

Courses
NOTE: See Appendix B for additional course information

- *Nuclear Physics/Radiation Monitoring* -- DOE
- DOE/EH-0450 (Revision 0), *Radiological Assessors Training (for Auditors and Inspectors) - Fundamental Radiological Control*, sponsored by the Office of Defense Programs, DOE
- *Applied Health Physics* -- Oak Ridge Institute for Science and Education
- *Health Physics for the Industrial Hygienist* -- Oak Ridge Institute for Science and Education
- *Radiological Worker Training* -- DOE-EH
- *Radiological Control Technician Training* -- DOE-EH
- *Safe Use of Radionuclides* -- Oak Ridge Institute for Science and Education
- *Radiation Protection General Technical Base Qualification Standard Training* -- GTS Duratek

NOTES: