Course Title: **Radiological Control Technician**
Module Title: **Radiation Detector Theory**
Module Number: **1.13**

Objectives:

1.13.01 Identify the three fundamental laws associated with electrical charges.

1.13.02 Identify the definition of current, voltage and resistance and their respective units.

1.13.03 Select the function of the detector and readout circuitry components in a radiation measurement system.

1.13.04 Identify the parameters that affect the number of ion pairs collected in a gas-filled detector.

1.13.05 Given a graph of the gas amplification curve, identify the regions of the curve.

1.13.06 Identify the characteristics of a detector operated in each of the useful regions of the gas amplification curve.

1.13.07 Identify the definition of the following terms:
- a. Resolving time
- b. Dead time
- c. Recovery time

1.13.08 Identify the methods employed with gas-filled detectors to discriminate between various types of radiation and various radiation energies.

1.13.09 Identify how a scintillation detector and associated components operate to detect and measure radiation.

1.13.10 Identify how neutron detectors detect neutrons and provide an electrical signal.

1.13.11 Identify the principles of detection, advantages and disadvantages of a GeLi detector and an HPGe detector.

References:

1. "Basic Radiation Protection Technology"; Gollnick, Daniel; Pacific Radiation Press; 1983
2. ANL-88-26 (1988) "Operational Health Physics Training"; Moe, Harold; Argonne National Laboratory, Chicago
3. "Radiation Detection and Measurement"; Knoll, Glenn F. John; Wiley & Sons; 1979

Instructional Aids:

1. Overheads
2. Overhead projector/screen
3. Chalkboard/whiteboard
4. Lessons learned

I. MODULE INTRODUCTION

A. Self-Introduction

1. Name

2. Phone number

3. Background

4. Emergency procedure review

B. Motivation

It is necessary for an RCT to have a good theoretical understanding of radiological instrumentation. This will help them to understand the data obtained by that instrumentation.

C. Overview of Lesson

1. Sources of Electrical Energy

2. Basic Electrical Quantities

3. Measurement systems

4. Detectors

5. Readout Circuitry

6. Detector yield

7. Various detectors

D. Introduce Objectives

O.H.: Objectives

II. MODULE OUTLINE

A. Sources of Electrical Energy

1. All matter composed of atoms

a. Protons

1) Positive charge

2) In nucleus

b. Electrons

1) Negative charge

2) Orbit nucleus

2. Fundamental laws for electrical charges

Objective 1.13.01

a. Opposite electrical charges of equal value cancel each other out.

b. Opposite electrical charges attract each other.

c. Like electrical charges repel each other.

3. Electric current is movement of electrons

a. Energy required to remove from orbit

b. If low, conductor

c. If high, insulator

4. Seven sources of energy

a. Friction: Static electricity - The rubbing causes electrons to leave one material and move to the other. As the electrons are transferred, a positive charge builds up on the material that is losing electrons, and a negative charge builds up on the material that is gaining electrons.

b. Heat: Thermocouples - The design of a thermocouple is based on the fact that heat will cause a small amount of electricity to move across the junction of two dissimilar metals.

c. Pressure: Piezoelectric effect - Pressure can be applied to certain types of crystals to produce electricity. The application of pressure to such crystals releases electrons from their orbits and thus causes current to flow.

d. Light: Photoelectric effect - In some materials, light can cause atoms to release electrons, when this happens, current flows through the material.

e. Chemical action: Batteries - Certain types of chemical reactions create electricity by separating the positive and negative charges in atoms. Batteries depend on chemical reactions to produce electricity.

f. Magnetism: Generators - Generators use an effect of magnetism called magnetic induction to produce electric current. Magnetic induction is the generation of electric current in a conductor due to the relative motion between the conductor and a magnetic field.

g. Ionizing Radiation: Radiation can remove electrons from atoms and thereby create a flow of electrons or current.

1) Alpha radiation

2) Beta radiation

3) Gamma radiation

B. Basic Electrical Quantities — Objective 1.13.02

1. Current

a. A measure of the movement or flow of electrons past a point in a circuit

b. 1 amp = 6.24×10^{18} electrons/second = 1 coulomb/second

c. DC = one way

d. AC = alternating

2. Voltage

a. A measure of electrical potential energy force that causes current flow

b. Measured in volts

3. Resistance

a. Measure of the opposition to electron flow in a circuit

b. Measured in ohms

c. Very high in insulators

d. Very low in conductors

4. Ohm's Law

a. I = E/R

b. E = IR

c. R = E/I

where:

E = voltage (volts)

I = current (amps)

R = resistance (ohms)

C. Measurement Systems

Objective 1.13.03

1. Measurement/Detection

See Fig. 1 - "Basic Radiation Measurement System"

a. Radiation type

b. Radiation intensity

c. Applications

2. Detector function - The incident radiation interacts with the detector material to produce an observable effect, be it a chemical change or an electrical signal.

3. Readout circuitry function - measures and analyzes the produced effect in the detector and provides a usable output signal and/or indication.

D. Detectors

1. Detection process

2. Types

a. Ionization Detectors - In ionization detectors, the incident radiation creates ion pairs in the detector.

1) Gas-filled

2) Solid

b. Excitation detectors - In excitation detectors, the incident radiation excites the atoms of the detector material. The atoms give off the excess energy in the form of visible light.

c. Chemical detectors - In chemical detectors, the incident radiation causes ionization or excitation of the detector media thereby causing chemical changes which can be analyzed.

d. Other detectors - Some detectors use other methods of detection, e.g., Cerenkov, Activation Foils, or Biological.

E. Readout Circuitry

1. Measurement process

2. Types

a. Ratemeter

1) Electric Pulse Output measures the effect of single events in a system. The output consists of several signals resolved in time.

2) Current Output measures the average effect due to a large number of interactions in the system.

b. Counter

F. Detector Yield

1. As all detectors measure radiation as a function of its observed effects, a correlation must be made between the effect and the incident radiation.

2. Factors

a. Detector size and shape

b. Detector material characteristics

c. Radiation energy

d. Probability of ionization

G. Gas-Filled Detectors

1. Basic construction

See Fig. 2 - "Basic Gas-filled Detector"

a. Detector gas - The gas used in the detector can be almost any gaseous mixture which will ionize, including air. Some ionization detectors, particularly ionization chambers use only air, while other detectors use gas mixtures that ionize more readily to obtain the desired detector response.

b. Electrodes - The cylinder walls are usually used as one electrode and an axial wire mounted in the center is used as the other electrode. Insulators support the axial electrode.

c. H.V. supply - Could be either batteries or alternating current.

2. Basic theory

a. Ion pair production - Created when ionizing radiation interacts with the detector gas.

b. Ion pair collection - When a voltage potential is established across the two electrodes the ion pairs will be attracted to the respective electrode with the opposite charge.

c. Analysis - The amount of current flow is representative of the energy and number of radiation events that caused ionization. The readout circuitry analyzes this current and provides an indication of the amount of radiation that has been detected.

d. Ion pair production factors

Objective 1.13.04

1) Type of radiation - A radiation with a high specific ionization, such as alpha, will produce more ion pairs in each centimeter that it travels than will a radiation with a low specific ionization such as gamma.

2) Energy of the radiation - The probability of interaction between the incident particle radiation and the detector gas (and therefore the production of ions) decreases with increasing radiation energy. In photon interactions, the overall probability of interaction increases, because of the increasing contribution of the pair production reactions.

See Table 1 - "Specific Ionization in Air at STP"

3) Quantity of radiation - As the number of radiation events striking a detector increases, the overall probability of an interaction occurring with the formation of an ion pair increases.

4) Detector size and shape - A larger detector volume offers more "targets" for the incident radiation, resulting in a larger number of ion pairs.

5) Type of detector gas - The ionization potential is expressed in units of electron volts per ion pair and is called the W-Value. Typical gases have values of 25-50 eV, with an average of about 34 eV per ion pair.

6) Detector gas pressure and composition - Instead of increasing detector size to increase the number of "target" atoms, increasing the pressure of the gas will accomplish the same goal.

7) Voltage potential across the electrodes - If left undisturbed, the ion pairs will recombine, and not be collected. If a field is created in the detector by applying a voltage potential across the electrodes, the ion pairs will be accelerated towards the electrodes.

Objective 1.13.05
See Fig. 3 - "Six-region Curve for Gas-filled Detectors"

8) Effect of voltage potential on detector processes - If the applied voltage potential is varied from 0 to a high value, and the pulse size is recorded and graphed, a response curve will be observed. The ion chamber region, the proportional region, and the Geiger-Mueller region are useful for detector designs used in radiological control. Other regions, the recombination region, the limited proportional region, and the continuous discharge region, are not useful.

9) Materials

3. Ion chamber detectors

   a. Operation/design — Objective 1.13.06

      1) All primary ions created are collected before they can recombine, called Saturation Current.

      2) No secondary ions created, no gas amplification occurs.

   b. Advantages

      1) Less regulated power supplies

      2) Response proportional to dose rate

   c. Disadvantages

      1) Sensitivity poor

         a) Small output current

         b) 2 E-14 amps per mr/hr

      2) Affected by humidity

         a) High impedance

         b) Leakage paths

      3) Affected by temp/at pressure

         a) Typically 2% for 10 ◦F

         b) 4.6% per psig

   d. Typical applications

      1) Dose rate instruments

      2) Installed monitors

         a) ARMS

         b) PRMS

4. Proportional detectors

   a. Operation/design — Objective 1.13.06

      1) Secondary ionization - such output is still proportional to input.

      2) Primary ions cause amplification of signal due to secondary ionization of gas.

         a) As the voltage on the detector is increased beyond the ion chamber region, the ions created by primary ionization are accelerated by the electric field towards the electrode.

         b) The primary ions gain enough energy in the acceleration to produce secondary ionization pairs. These newly formed secondary ions are also accelerated, causing additional ionizations.

      3) Large output pulses - The large number of events, known as an avalanche, create a single, large electrical pulse.

      4) Discrimination - Since we can measure the individual pulse, it is possible to analyze both the rate of incidence and the energy or type of radiation with a proportional counter. This allows for discrimination of different types of radiation or different radiation energies by varying the high voltage (which affects the gas amplification factor). — Objective 1.13.07

         a) Resolving time - the total time from a measurable detector response before another pulse can be measured.

   b. Detector construction

      1) Cylindrical detectors

         a) Portable survey instrument

         b) BF_3 or P-10 gas

2) Window, 2pi gas flow

See Fig. 4 - "Basic 2π Proportional Detector w/ Window"

a) P-10 gas

3) Windowless, 2pi gas flow

4) 4pi gas flow

5) Gas flow, flat

c. Advantages

1) Good discrimination

2) Good sensitivity

3) Useful for dose rates

d. Disadvantages

1) Requires highly regulated power supplies

5. Geiger-Mueller detectors

a. Operation/design

1) Resolving time is the time from the initial measured pulse until another pulse can be measured by the electronics. Resolving time is controlled by the electronics package.

2) Dead time is the time from the initial pulse until another pulse can be produced.

Objective 1.13.07
See Fig. 5 - "Dead Time of a G-M Tube"

3) Recovery time is the time from the initial full size pulse to the next full size pulse, not including the dead time.

4) Sequence of events

a) Ion pair (IP) produced

b) IP acceleration toward electrode

c) Secondary ionization

d) Avalanche

e) Negative ions collected at center electrode, start of dead time

f) Positive ion cloud drifts toward shell

g) Voltage potential increases

h) End of dead time, start of recovery time

i) Amplification/ pulse size increases

j) End of recovery and resolving time

b. Effects of long resolving time

1) Reduced accuracy

2) Unusable in high flux rates

c. GM detector construction

d. Advantages of GM

1) Not affected by temp/press - Not vented to the atmosphere and also due to the magnitude of the output pulse.

2) Less regulated power supplies.

3) More sensitive (for same size) - As the voltage is increased further, the secondary ions are also accelerated to very high velocities and gain sufficient energy to cause ionization themselves. These tertiary ionization's spread rapidly throughout the tube causing an avalanche. The avalanche, caused by a single ionization, results in a single very large pulse.

4) Simple electronics package.

e. Disadvantages of GM

1) Does not measure true dose - Detector response is not related to the energy deposited.

2) Typically large dead time - Activity present but undetected during dead time, resulting in a reduction of detector efficiency.

3) Cannot discriminate - The instrument will respond with a very large pulse regardless of the type or energy of radiation.

f. Typical applications (Insert site specific applications)

6. Discrimination

Objective 1.13.08

a. Purpose

1) Physical discrimination

a) Shielding is primary method of physical discrimination.

b) Shield has greater effect on lower energy gammas.

c) Shields can stop all alpha and beta.

2) Detector gas fill

a) Each type of radiation has a specific ionization factor in a particular gas.

b) In addition, each different detector gas has a different response to various radiation energies.

c) By employing the most advantageous gas, a detector can be constructed that will have a higher yield for a specific radiation type or radiation energy than it will for other radiation types or energies.

3) Electronic discrimination

a) Discriminator low level

- Input sensitivity

- Rejects low level pulses

b) Pulse height is used to discriminate between types and energy of radiation.

c) A GM detector cannot be used to electronically discriminate between types of radiation because all output pulses are of the same height.

H. Scintillation Detectors

Objective 1.13.09

1. Scintillation process

a. Scintillation detector materials

1) The scintillation material converts radiation energy to a visible light output by excitation of the material.

2) Phosphors and fluors

a) Organic Crystals - In organic crystals, the incident radiation raises the molecules of the phosphor to a higher energy state. Upon decay back to the ground state, these molecules emit light.

b) Organic Liquids - The incident radiation will interact with the molecules of the liquid solvent, exciting those molecules. The molecules transfer their energy to the organic solute molecules suspended in the solvent. The molecules of the solute return to the ground state by emission of a light photon.

c) Inorganic Crystals - An incident photon interacts with the crystal atoms (NaI) exciting the atom and raising valence band electrons to the conductance band, leaving a "hole" in the valence band.

- Some of these electrons and holes recombine to form an "exciton." The excitons, free holes, and free electrons drift through the crystal.

- The impurity centers (T1) capture the excitons, free holes, and free electrons. This capture raises the impurity center to an excited state.

- The impurity center will decay back to the ground state, and in doing so, emits a light photon, which is proportional to the energy of the incident radiation.

d) Inorganic Powders - Operate with a mechanism similar to that of inorganic crystals.

b. Photomultiplier Tubes/Photocathode

See Fig. 6 - "Photomultiplier Detector"

Construction

1) The photocathode converts light output to photo electrons

2) The photomultiplier tube converts photoelectrons to an amplified electrical signal

2. Applications

a. NaI(TI) - Commonly used in applications where high gamma sensitivity and a high energy resolution is desired.

b. Liquid scintillator - Used in applications where it is desired to measure radiation of low energy or low penetrating ability.

3. Advantages

a. Discrimination - Ability to discriminate between alpha, beta, gamma radiations and between different radiation energies with a moderate resolution.

b. High Gamma Sensitivity (NaI(TI))

c. Low energy response (liquid)

d. Alpha detection (ZnS(Ag))

4. Disadvantages

a. Poor low energy gamma response it has no alpha or beta response.(NaI(Tl))

b. Cumbersome and solution is one time use only (liquid)

c. Regulate power supply for pulse height analysis

d. Fragile (NaI(Tl)), (ZnS(Ag))

I. Neutron Detection — Objective 1.13.10

1. Slow neutrons

a. Boron activation

1) The neutron is absorbed by a ^{10}B atom which decays to a ^{9}Li atom and an alpha particle.

2) The alpha causes ionization; gas amplification provides a usable electrical signal.

b. Fission Chamber - A slow neutron will cause an atom of U-235 to fission, with the two fission fragments produced having a high kinetic energy and causing ionization in the material they pass through. Thus, by coating one of the electrodes of an ionization chamber with a thin layer of uranium enriched in U-235, a detector sensitive to slow neutrons is formed.

c. Scintillation - Scintillation detectors can be designed to detect slow neutrons by incorporating boron or lithium in the scintillation crystal. The neutrons interact with the boron or lithium atoms to produce an alpha particle, which then produces ionization and scintillation.

d. Thermoluminescence - Thermoluminescent dosimeters can be designed to detect slow neutrons by incorporating lithium-6 in the crystal.

e. Activation foils - Various materials have the ability to absorb neutrons of a specific energy and become radioactive through the radiative capture process. By measuring the radioactivity of thin foils such as gold, silver or indium, we can determine the amount of neutrons to which the foils were exposed.

Commercially available criticality accident dosimeters often utilize this method.

2. Fast neutrons

a. Proton recoil (ion chamber/proportional) - When fast neutrons undergo elastic scatterings with hydrogen atoms, they frequently strike the hydrogen atom with enough force to knock the proton nucleus away from the orbiting electron. This energetic proton then produces ionization which can be measured. Most devices for measuring fast neutrons use an ionization detector operated in either the ion chamber or proportional region.

b. Thermalization - One technique for measuring fast neutrons is to convert them to slow neutrons. In this technique, a sheet of cadmium is placed on the outside of the detector to absorb any slow neutrons. A thickness of paraffin, or another good moderator, is placed under the cadmium to convert the fast neutrons into slow ones. One of the slow neutron detectors is positioned inside the paraffin to measure the slow neutrons, thereby measuring the original fast neutrons.

c. Application - BF_3 neutron detector — See Table 2 - "Neutron Flux/Dose Relationship"

1) Neutron flux/dose relationship

2) Neutron detector energy response curve

J. Semi-Conductor

1. Principles of operation — Objective 1.13.11

a. Rely on the collection of electron-hole pairs from the detector to produce a usable electrical signal. — See Figs. 7 - 11

2. GeLi system

a. Advantages

1) high resolution

2) shorter response time and more linear response than NaI (Tl) detector

3) small crystals offer best resolution

b. Disadvantages

1) only used for photon detection

2) must be cooled at all times

3) lower efficiency than NaI

4) long counting times for environmental samples

3. Intrinsic (HP) germanium detectors

   a. Differences between GeLi and HPGe

      1) Principles of operation

   b. Advantages of HPGe's

      1) Stored at room temperature (with no voltage applied)

      2) More portable

   c. Disadvantages of HPGe's

      1) Operation needs liquid nitrogen

      2) Expense

   d. Applications

      1) Portable MCA's

      2) Same as GeLi

4. Applications (MCA) - Gamma Spectroscopy System

K. Condenser R-Meter/Chamber

   1. Method of detection - The condenser chamber is an integrating, air wall tissue equivalent ionization chamber used to measure exposure to X or gamma radiation.

      a. Two Functions - The Condenser R-Meter performs two functions. It applies a charge to the chamber and, after exposure, serves as a read-out device to determine the amount of exposure.

   2. Range - Condenser chambers vary in size. The total measured exposure in a chamber decreases as the volume increases. Chambers are generally available which enable us to cover exposure ranges from several mR up to 250 R.

3. Energy response - Condenser chambers vary in material and thickness as well as in size. The choice of wall material and thickness off-sets the energy dependence of the chambers.

4. Applications - The condenser chambers are generally used to calibrate X and gamma radiation sources, and for making surveys of X-ray equipment. Condenser chambers may also be used to measure neutron radiation. Some chambers are boron lined and measure the ionization from the alpha particles emitted in the boron-thermal neutron reaction.

III. SUMMARY

A. Review major topics

1. Sources of Electrical Energy
2. Basic Electrical Quantities
3. Measurement systems
4. Detectors
5. Readout Circuitry
6. Detector yield
7. Various detectors

B. Review learning objectives

IV. EVALUATION

Evaluation should consist of a written examination comprised of multiple choice questions. 80% should be the minimum passing criteria for the examination.