

**Department of Energy  
Fundamentals Handbook**

**INSTRUMENTATION AND CONTROL  
Module 6  
Radiation Detectors**



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## TABLE OF CONTENTS

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LIST OF FIGURES . . . . .	iv
LIST OF TABLES . . . . .	vi
REFERENCES . . . . .	vii
OBJECTIVES . . . . .	viii
RADIATION DETECTION TERMINOLOGY . . . . .	1
Electron-Ion Pair . . . . .	1
Specific Ionization . . . . .	1
Stopping Power . . . . .	2
Summary . . . . .	3
RADIATION TYPES . . . . .	4
Alpha Particle . . . . .	4
Beta Particle . . . . .	5
Gamma Ray . . . . .	6
Neutron . . . . .	8
Summary . . . . .	10
GAS-FILLED DETECTOR . . . . .	11
Summary . . . . .	13
DETECTOR VOLTAGE . . . . .	14
Applied Voltage . . . . .	14
Summary . . . . .	18
PROPORTIONAL COUNTER . . . . .	19
Summary . . . . .	22

---

**TABLE OF CONTENTS (Cont.)**

---

PROPORTIONAL COUNTER CIRCUITRY .....	23
Summary .....	27
IONIZATION CHAMBER .....	28
Summary .....	34
COMPENSATED ION CHAMBER .....	35
Summary .....	39
ELECTROSCOPE IONIZATION CHAMBER .....	40
Summary .....	41
GEIGER-MÜLLER DETECTOR .....	42
Summary .....	44
SCINTILLATION COUNTER .....	45
Summary .....	48
GAMMA SPECTROSCOPY .....	49
Summary .....	50
MISCELLANEOUS DETECTORS .....	51
Self-Powered Neutron Detector .....	51
Wide Range Fission Chamber .....	52
Activation Foils and Flux Wires .....	53
Photographic Film .....	53
Summary .....	54

---

**TABLE OF CONTENTS (Cont.)**

---

CIRCUITRY AND CIRCUIT ELEMENTS . . . . .	55
Terminology . . . . .	55
Components . . . . .	57
Summary . . . . .	62
SOURCE RANGE NUCLEAR INSTRUMENTATION . . . . .	63
Summary . . . . .	65
INTERMEDIATE RANGE NUCLEAR INSTRUMENTATION . . . . .	66
Summary . . . . .	68
POWER RANGE NUCLEAR INSTRUMENTATION . . . . .	69
Summary . . . . .	71

---

**LIST OF FIGURES**

---

Figure 1	Alpha Particle Specific Ionization -vs- Distance Traveled in Air . . . . .	5
Figure 2	Photoelectric Effect . . . . .	6
Figure 3	Compton Scattering . . . . .	6
Figure 4	Pair Production . . . . .	7
Figure 5	Schematic Diagram of a Gas-Filled Detector . . . . .	11
Figure 6	Ion Pairs Collected -vs- Applied Voltage . . . . .	15
Figure 7	Proportional Counter . . . . .	19
Figure 8	Gas Ionization Curve . . . . .	20
Figure 9	Proportional Counter Circuit . . . . .	23
Figure 10	Single Channel Analyzer Operation . . . . .	24
Figure 11	Single Channel Analyzer Output . . . . .	25
Figure 12	Discriminator . . . . .	26
Figure 13	BF <sub>3</sub> Proportional Counter Circuit . . . . .	26
Figure 14	Simple Ionization Circuit . . . . .	29
Figure 15	Recombination and Ionization Regions . . . . .	30
Figure 16	Ionization Chamber . . . . .	31
Figure 17	Minimizing Gamma Influence by Size and Volume . . . . .	32
Figure 18	Minimizing Gamma Influence with Boron Coating Area . . . . .	33
Figure 19	Compensated Ion Chamber . . . . .	35

---

**LIST OF FIGURES (Cont.)**

---

Figure 20	Compensated Ion Chamber with Concentric Cylinders . . . . .	36
Figure 21	Typical Compensation Curve . . . . .	38
Figure 22	Quartz Fiber Electroscope . . . . .	40
Figure 23	Gas Ionization Curve . . . . .	42
Figure 24	Electronic Energy Band of an Ionic Crystal . . . . .	45
Figure 25	Scintillation Counter . . . . .	46
Figure 26	Photomultiplier Tube Schematic Diagram . . . . .	47
Figure 27	Gamma Spectrometer Block Diagram . . . . .	49
Figure 28	Multichannel Analyzer Output . . . . .	50
Figure 29	Self-Powered Neutron Detector . . . . .	51
Figure 30	Analog and Digital Displays . . . . .	56
Figure 31	Single and Two-Stage Amplifier Circuits . . . . .	58
Figure 32	Biased Diode Discriminator . . . . .	59
Figure 33	Log Count Rate Meter . . . . .	60
Figure 34	Period Meter Circuit . . . . .	61
Figure 35	Source Range Channel . . . . .	64
Figure 36	Intermediate Range Channel . . . . .	67
Figure 37	Power Range Channel . . . . .	70

## **LIST OF TABLES**

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## TERMINAL OBJECTIVE

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- 1.0 **SUMMARIZE** radiation protection principles to include definition of terms, types of radiation, and the basic operation of a gas-filled detector.

## ENABLING OBJECTIVES

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- 1.1 **DEFINE** the following radiation detection terms:
- Electron-ion pair
  - Specific ionization
  - Stopping power
- 1.2 **EXPLAIN** the relationship between stopping power and specific ionization.
- 1.3 **DESCRIBE** the following types of radiation to include the definition and interactions with matter.
- Alpha ( $\alpha$ )
  - Beta ( $\beta$ )
  - Gamma ( $\gamma$ )
  - Neutron (n)
- 1.4 **DESCRIBE** the principles of operation of a gas-filled detector to include:
- How the electric field affects ion pairs
  - How gas amplification occurs
- 1.5 Given a diagram of an ion pairs collected -vs- detector voltage curve, **DESCRIBE** the regions of the curve to include:
- The name of the region
  - Interactions taking place within the gas of the detector
  - Difference between the alpha and beta curves, where applicable

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## TERMINAL OBJECTIVE

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- 2.0 **SUMMARIZE** the principles of operation of various types of radiation detectors.

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## ENABLING OBJECTIVES

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- 2.1 **DESCRIBE** the operation of a proportional counter to include:
- Radiation detection
  - Quenching
  - Voltage variations
- 2.2 Given a block diagram of a proportional counter circuit, **STATE** the purpose of the following major blocks:
- Proportional counter
  - Preamplifier/amplifier
  - Single channel analyzer/discriminator
  - Scaler
  - Timer
- 2.3 **DESCRIBE** the operation of an ionization chamber to include:
- Radiation detection
  - Voltage variations
  - Gamma sensitivity reduction
- 2.4 **DESCRIBE** how a compensated ion chamber compensates for gamma radiation.
- 2.5 **DESCRIBE** the operation of an electroscope ionization chamber.
- 2.6 **DESCRIBE** the operation of a Geiger-Müller (G-M) detector to include:
- Radiation detection
  - Quenching
  - Positive ion sheath
- 2.7 **DESCRIBE** the operation of a scintillation counter to include:
- Radiation detection
  - Three classes of phosphors
  - Photomultiplier tube operation

## **ENABLING OBJECTIVES (Cont.)**

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- 2.8 **DESCRIBE** the operation of a gamma spectrometer to include:
- a. Type of detector used
  - b. Multichannel analyzer operation
- 2.9 **DESCRIBE** how the following detect neutrons:
- a. Self-powered neutron detector
  - b. Wide range fission chamber
  - c. Flux wire
- 2.10 **DESCRIBE** how a photographic film is used to measure the following:
- a. Total radiation dose
  - b. Neutron dose

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## TERMINAL OBJECTIVE

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- 3.0 **SUMMARIZE** the operation of typical source, intermediate, and power range nuclear instruments.

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## ENABLING OBJECTIVES

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- 3.1 **DEFINE** the following terms:
- Signal-to-noise ratio
  - Discriminator
  - Analog
  - Logarithm
  - Period
  - Decades per minute (DPM)
  - Scalar
- 3.2 **LIST** the type of detector used in each of the following nuclear instruments:
- Source range
  - Intermediate range
  - Power range
- 3.3 Given a block diagram of a typical source range instrument, **STATE** the purpose of major components.
- Linear amplifier
  - Discriminator
  - Pulse integrator
  - Log count rate amplifier
  - Differentiator
- 3.4 Given a block diagram of a typical intermediate range instrument, **STATE** the purpose of major components.
- Log n amplifier
  - Differentiator
  - Reactor protection interface
- 3.5 **STATE** the reason gamma compensation is NOT required in the power range.
- 3.6 Given a block diagram of a typical power range instrument, **STATE** the purpose of major components.
- Linear amplifier
  - Reactor protection interface

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## RADIATION DETECTION TERMINOLOGY

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*Understanding how radiation detection occurs requires a working knowledge of basic terminology.*

**EO 1.1      DEFINE the following radiation detection terms:**

- a.      Electron-ion pair**
- b.      Specific ionization**
- c.      Stopping power**

**EO 1.2      EXPLAIN the relationship between stopping power and specific ionization.**

---

### **Electron-Ion Pair**

Ionization is the process of removing one or more electrons from a neutral atom. This results in the loss of units of negative charge by the affected atom. The atom becomes electrically positive (a positive ion). The products of a single ionizing event are called an electron-ion pair.

### **Specific Ionization**

Specific ionization is that number of ion pairs produced per centimeter of travel through matter. Equation 6-1 expresses this relationship.

$$\text{Specific Ionization} = \frac{\text{ion pairs produced}}{\text{path length}} \quad (6-1)$$

Specific ionization is dependent on the mass, charge, energy of the particle, and the electron density of matter. The greater the mass of a particle, the more interactions it produces in a given distance. A larger number of interactions results in the production of more ion pairs and a higher specific ionization.

A particle's charge has the greatest effect on specific ionization. A higher charge increases the number of interactions which occur in a given distance. Increasing the number of interactions produces more ion pairs, therefore increasing the specific ionization.

As the energy of a particle decreases, it produces more ion pairs for the same amount of distance traveled. Think of the particle as a magnet. As a magnet is passed over a pile of paper clips, the magnet attracts the clips. Maintain the same distance from the pile and vary the speed of the magnet. Notice that the slower the magnet is passed over the pile of paper clips, the more

clips become attached to the magnet. The same is true of a particle passing by a group of atoms at a given distance. The slower a particle travels, the more atoms it affects.

### **Stopping Power**

Stopping power or linear energy transfer (LET) is the energy lost per unit path length. Equation 6-2 expresses this relationship.

$$S = \text{LET} = \frac{\Delta E}{\Delta X} \quad (6-2)$$

where

- S = stopping power
- LET = linear energy transfer
- $\Delta E$  = energy lost
- $\Delta X$  = path length of travel

Specific ionization times the energy per ion pair yields the stopping power (LET), as shown in Equation 6-3.

$$\begin{aligned} S &= \left( \frac{\text{ion pairs}}{\text{path length}} \right) \left( \frac{\text{energy}}{\text{ion pairs}} \right) \\ &= \frac{\text{energy}}{\text{path length}} \end{aligned} \quad (6-3)$$

Stopping power, or LET, is proportional to the specific ionization.

## **Summary**

Stopping power is proportional to specific ionization. Radiation detection terms discussed in this chapter are summarized below.

### **Radiation Detection Terms Summary**

- An electron-ion pair is the product of a single ionizing event.
- Specific ionization is that number of ion pairs produced per centimeter of travel through matter.
- Stopping power is the energy lost per unit path length.

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## RADIATION TYPES

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*The four types of radiation discussed in this chapter are alpha, beta, gamma, and neutron.*

**EO 1.3**      **DESCRIBE the following types of radiation to include the definition and interactions with matter.**

- a.      **Alpha ( $\alpha$ )**
  - b.      **Beta ( $\beta$ )**
  - c.      **Gamma ( $\gamma$ )**
  - d.      **Neutron (**n**)**
- 

### Alpha Particle

The alpha particle is a helium nucleus produced from the radioactive decay of heavy metals and some nuclear reactions. Alpha decay often occurs among nuclei that have a favorable neutron/proton ratio, but contain too many nucleons for stability. The alpha particle is a massive particle consisting of an assembly of two protons and two neutrons and a resultant charge of +2.

Alpha particles are the least penetrating radiation. The major energy loss for alpha particles is due to electrical excitation and ionization. As an alpha particle passes through air or soft tissue, it loses, on the average, 35 eV per ion pair created. Due to its highly charged state, large mass, and low velocity, the specific ionization of an alpha particle is very high.

Figure 1 illustrates the specific ionization of an alpha particle, on the order of tens of thousands of ion pairs per centimeter in air. An alpha particle travels a relatively straight path over a short distance.

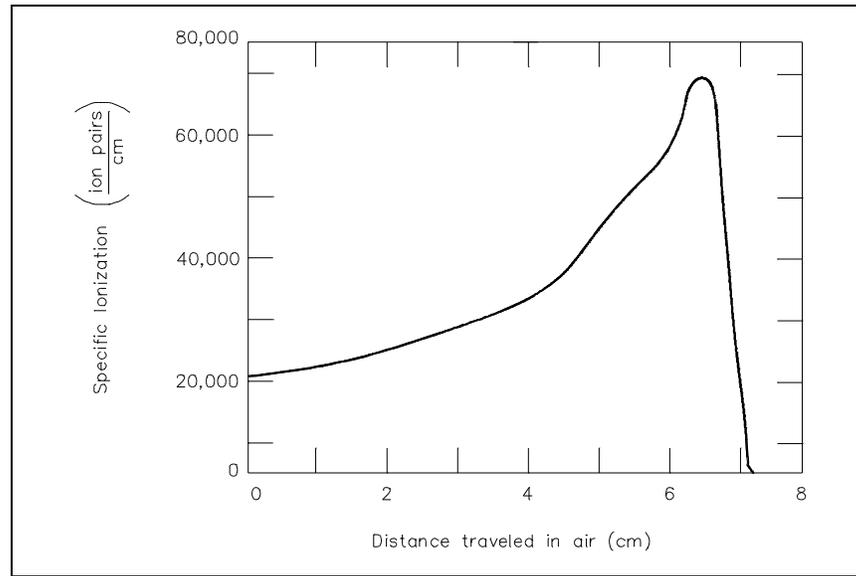


Figure 1 Alpha Particle Specific Ionization -vs- Distance Traveled in Air

## **Beta Particle**

The beta particle is an ordinary electron or positron ejected from the nucleus of a beta-unstable radioactive atom. The beta has a single negative or positive electrical charge and a very small mass.

The interaction of a beta particle and an orbital electron leads to electrical excitation and ionization of the orbital electron. These interactions cause the beta particle to lose energy in overcoming the electrical forces of the orbital electron. The electrical forces act over long distances; therefore, the two particles do not have to come into direct contact for ionization to occur.

The amount of energy lost by the beta particle depends upon both its distance of approach to the electron and its kinetic energy. Beta particles and orbital electrons have the same mass; therefore, they are easily deflected by collision. Because of this fact, the beta particle follows a tortuous path as it passes through absorbing material. The specific ionization of a beta particle is low due to its small mass, small charge, and relatively high speed of travel.

## Gamma Ray

The gamma ray is a photon of electromagnetic radiation with a very short wavelength and high energy. It is emitted from an unstable atomic nucleus and has high penetrating power.

There are three methods of attenuating (reducing the energy level of) gamma-rays: photoelectric effect, Compton scattering, and pair production.

The photoelectric effect occurs when a low energy gamma strikes an orbital electron, as shown in Figure 2. The total energy of the gamma is expended in ejecting the electron from its orbit. The result is ionization of the atom and expulsion of a high energy electron.

The photoelectric effect is most predominant with low energy gammas and rarely occurs with gammas having an energy above 1 MeV (million electron volts).

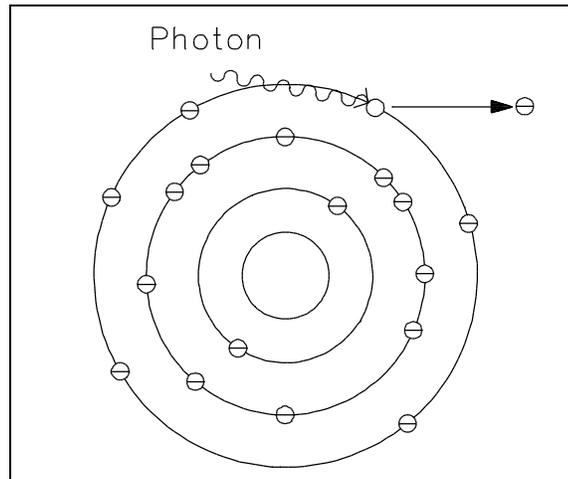


Figure 2 Photoelectric Effect

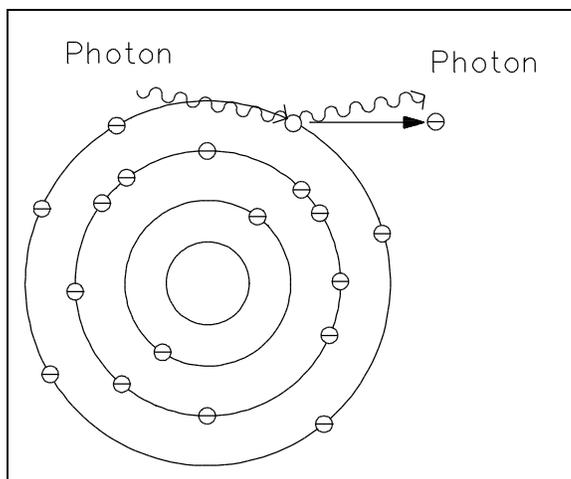


Figure 3 Compton Scattering

Compton scattering is an elastic collision between an electron and a photon, as shown in Figure 3. In this case, the photon has more energy than is required to eject the electron from orbit, or it cannot give up all of its energy in a collision with a free electron. Since all of the energy from the photon cannot be transferred, the photon must be scattered; the scattered photon must have less energy, or a longer wavelength. The result is ionization of the atom, a high energy beta, and a gamma at a lower energy level than the original.

Compton scattering is most predominant with gammas at an energy level in the 1.0 to 2.0 MeV range.

At higher energy levels, pair production is predominate. When a high energy gamma passes close enough to a heavy nucleus, the gamma disappears, and its energy reappears in the form of an electron and a positron (same mass as an electron, but has a positive charge), as shown in Figure 4. This transformation of energy into mass must take place near a particle, such as a nucleus, to conserve momentum. The kinetic energy of the recoiling nucleus is very small; therefore, all of the photon's energy that is in excess of that needed to supply the mass of the pair appears as kinetic energy of the pair. For this reaction to take place, the original gamma must have at least 1.02 MeV energy.

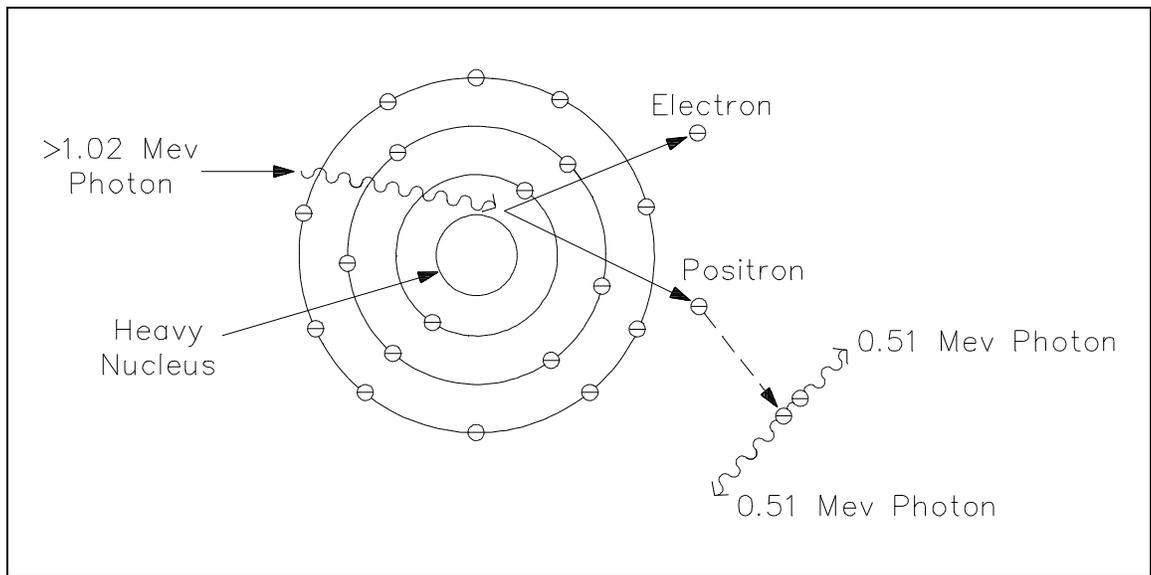


Figure 4 Pair Production

The electron loses energy by ionization. The positron interacts with other electrons and loses energy by ionizing them. If the energy of the positron is low enough, it will combine with an electron (mutual annihilation occurs), and the energy is released as a gamma. The probability of pair production increases significantly for higher energy gammas.

Gamma radiation has a very high penetrating power. A small fraction of the original stream will pass through several feet of concrete or several meters of air. The specific ionization of a gamma is low compared to that of an alpha particle, but is higher than that of a beta particle.

## Neutron

Neutrons have no electrical charge and have nearly the same mass as a proton (a hydrogen atom nucleus). A neutron is hundreds of times larger than an electron, but one quarter the size of an alpha particle. The source of neutrons is primarily nuclear reactions, such as fission, but they are also produced from the decay of radioactive elements. Because of its size and lack of charge, the neutron is fairly difficult to stop, and has a relatively high penetrating power.

Neutrons may collide with nuclei causing one of the following reactions: inelastic scattering, elastic scattering, radiative capture, or fission.

Inelastic scattering causes some of the neutron's kinetic energy to be transferred to the target nucleus in the form of kinetic energy and some internal energy. This transfer of energy slows the neutron, but leaves the nucleus in an excited state. The excitation energy is emitted as a gamma ray photon. The interaction between the neutron and the nucleus is best described by the compound nucleus mode; the neutron is captured, then re-emitted from the nucleus along with a gamma ray photon. This re-emission is considered the threshold phenomenon. The neutron threshold energy varies from infinity for hydrogen, (inelastic scatter cannot occur) to about 6 MeV for oxygen, to less than 1 MeV for uranium.

Elastic scattering is the most likely interaction between fast neutrons and low atomic mass number absorbers. The interaction is sometimes referred to as the "billiard ball effect." The neutron shares its kinetic energy with the target nucleus without exciting the nucleus.

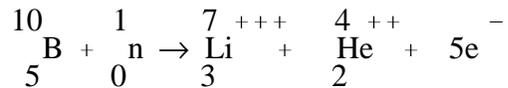
Radiative capture ( $n, \gamma$ ) takes place when a neutron is absorbed to produce an excited nucleus. The excited nucleus regains stability by emitting a gamma ray.

The fission process for uranium ( $U^{235}$  or  $U^{238}$ ) is a nuclear reaction whereby a neutron is absorbed by the uranium nucleus to form the intermediate (compound) uranium nucleus ( $U^{236}$  or  $U^{239}$ ). The compound nucleus fissions into two nuclei (fission fragments) with the simultaneous emission of one to several neutrons. The fission fragments produced have a combined kinetic energy of about 168 MeV for  $U^{235}$  and 200 MeV for  $U^{238}$ , which is dissipated, causing ionization. The fission reaction can occur with either fast or thermal neutrons.

The distance that a fast neutron will travel, between its introduction into the slowing-down medium (moderator) and thermalization, is dependent on the number of collisions and the distance between collisions. Though the actual path of the neutron slowing down is tortuous because of collisions, the average straight-line distance can be determined; this distance is called the fast diffusion length or slowing-down length. The distance traveled, once thermalized, until the neutron is absorbed, is called the thermal diffusion length.

Fast neutrons rapidly degrade in energy by elastic collisions when they interact with low atomic number materials. As neutrons reach thermal energy, or near thermal energies, the likelihood of capture increases. In present day reactor facilities the thermalized neutron continues to scatter elastically with the moderator until it is absorbed by fuel or non-fuel material, or until it leaks from the core.

Secondary ionization caused by the capture of neutrons is important in the detection of neutrons. Neutrons will interact with B-10 to produce Li-7 and He-4.



The lithium and alpha particles share the energy and produce "secondary ionizations" which are easily detectable.

## **Summary**

Alpha, beta, gamma, and neutron radiation are summarized below.

### **Radiation Types Summary**

#### Alpha particles

- The alpha particle is a helium nucleus produced from the radioactive decay of heavy metals and some nuclear reactions.
- The high positive charge of an alpha particle causes electrical excitation and ionization of surrounding atoms.

#### Beta particles

- The beta particle is an ordinary electron or positron ejected from the nucleus of a beta-unstable radioactive atom.
- The interaction of a beta particle and an orbital electron leads to electrical excitation and ionization of the orbital electron.

#### Gamma rays

- The gamma ray is a photon of electromagnetic radiation with a very short wavelength and high energy.
- The three methods of attenuating gamma-rays are: photoelectric effect, Compton scattering, and pair production.

#### Neutrons

- Neutrons have no electrical charge and have nearly the same mass as a proton (a hydrogen atom nucleus).
- Neutrons collide with nuclei, causing one of the following reactions: inelastic scattering, elastic scattering, radiative capture, or fission.

## GAS-FILLED DETECTOR

*A gas-filled detector is used to detect incident radiation.*

- EO 1.4      DESCRIBE the principles of operation of a gas-filled detector to include:**
- a.      How the electric field affects ion pairs**
  - b.      How gas amplification occurs**

The pulsed operation of the gas-filled detector illustrates the principles of basic radiation detection. Gases are used in radiation detectors since their ionized particles can travel more freely than those of a liquid or a solid. Typical gases used in detectors are argon and helium, although boron-trifluoride is utilized when the detector is to be used to measure neutrons. Figure 5 shows a schematic diagram of a gas-filled chamber with a central electrode.

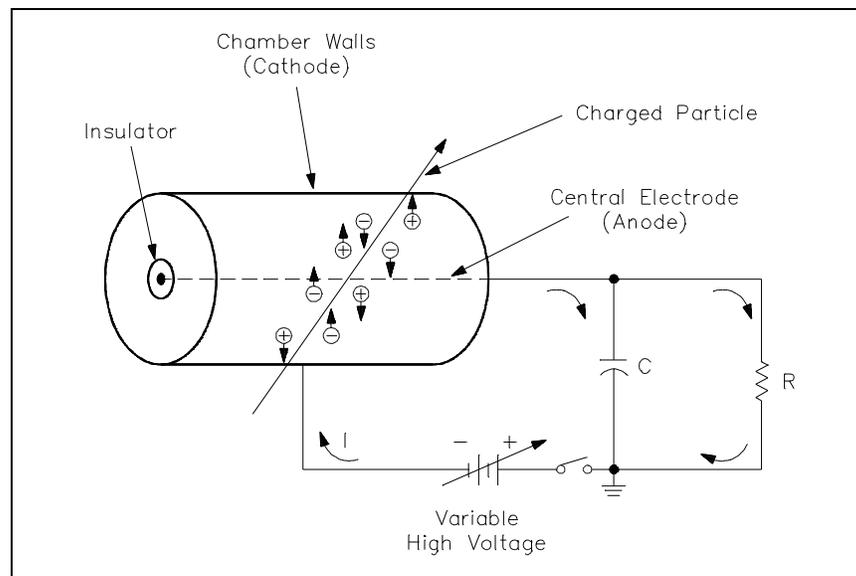


Figure 5 Schematic Diagram of a Gas-Filled Detector

The central electrode, or anode, collects negative charges. The anode is insulated from the chamber walls and the cathode, which collects positive charges. A voltage is applied to the anode and the chamber walls. The resistor in the circuit is shunted by a capacitor in parallel, so that the anode is at a positive voltage with respect to the detector wall. As a charged particle passes through the gas-filled chamber, it ionizes some of the gas (air) along its path of travel. The positive anode attracts the electrons, or negative particles. The detector wall, or cathode, attracts the positive charges. The collection of these charges reduces the voltage across the capacitor, causing a pulse across the resistor that is recorded by an electronic circuit. The voltage applied to the anode and cathode determines the electric field and its strength.

As detector voltage is increased, the electric field has more influence upon electrons produced. Sufficient voltage causes a cascade effect that releases more electrons from the cathode. Forces on the electron are greater, and its mean-free path between collisions is reduced at this threshold. Calculating the change in the capacitor's charge yields the height of the resulting pulse. Initial capacitor charge ( $Q$ ), with an applied voltage ( $V$ ), and capacitance ( $C$ ), is given by Equation 6-4.

$$Q = CV \quad (6-4)$$

A change of charge ( $\Delta Q$ ) is proportional to the change in voltage ( $\Delta V$ ) and equals the height of the pulse, as given by Equation 6-5 or 6-6.

$$\Delta Q = C\Delta V \quad (6-5)$$

$$\Delta V = \frac{\Delta Q}{C} \quad (6-6)$$

The total number of electrons collected by the anode determines the change in the charge of the capacitor ( $\Delta Q$ ). The change in charge is directly related to the total ionizing events which occur in the gas. The ion pairs ( $n$ ) initially formed by the incident radiation attain a great enough velocity to cause secondary ionization of other atoms or molecules in the gas. The resultant electrons cause further ionizations. This multiplication of electrons is termed gas amplification. The gas amplification factor ( $A$ ) designates the increase in ion pairs when the initial ion pairs create additional ion pairs. Therefore, the height of the pulse is given by Equation 6-7.

$$\Delta V = \frac{Ane}{C} \quad (6-7)$$

where

- $\Delta V$  = pulse height (volts)
- $A$  = gas amplification factor
- $n$  = initial ionizing events
- $e$  = charge of the electron ( $1.602 \times 10^{-19}$  coulombs)
- $C$  = detector capacitance (farads)

The pulse height can be computed if the capacitance, detector characteristics, and radiation are known. The capacitance is normally about  $10^{-4}$  farads. The number of ionizing events may be calculated if the detector size and specific ionization, or range of the charged particle, are known. The only variable is the gas amplification factor that is dependent on applied voltage.

### **Summary**

The operation of gas-filled detectors is summarized below.

#### **Gas-Filled Detectors Summary**

- The central electrode, or anode, attracts and collects the electron of the ion-pair.
- The chamber walls attract and collect the positive ion.
- When the applied voltage is high enough, the ion pairs initially formed accelerate to a high enough velocity to cause secondary ionizations. The resultant ions cause further ionizations. This multiplication of electrons is called gas amplification.

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## DETECTOR VOLTAGE

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*Different ranges of applied voltage result in unique detection characteristics.*

- EO 1.5**      **Given a diagram of an ion pairs collected -vs- detector voltage curve, DESCRIBE the regions of the curve to include:**
- a.      The name of the region**
  - b.      Interactions taking place within the gas of the detector**
  - c.      Difference between the alpha and beta curves, where applicable**
- 

### Applied Voltage

The relationship between the applied voltage and pulse height in a detector is very complex. Pulse height and the number of ion pairs collected are directly related. Figure 6 illustrates ion pairs collected -vs- applied voltage. Two curves are shown: one curve for alpha particles and one curve for beta particles; each curve is divided into several voltage regions. The alpha curve is higher than the beta curve from Region I to part of Region IV due to the larger number of ion pairs produced by the initial reaction of the incident radiation. An alpha particle will create more ion pairs than a beta since the alpha has a much greater mass. The difference in mass is negated once the detector voltage is increased to Region IV since the detector completely discharges with each initiating event.

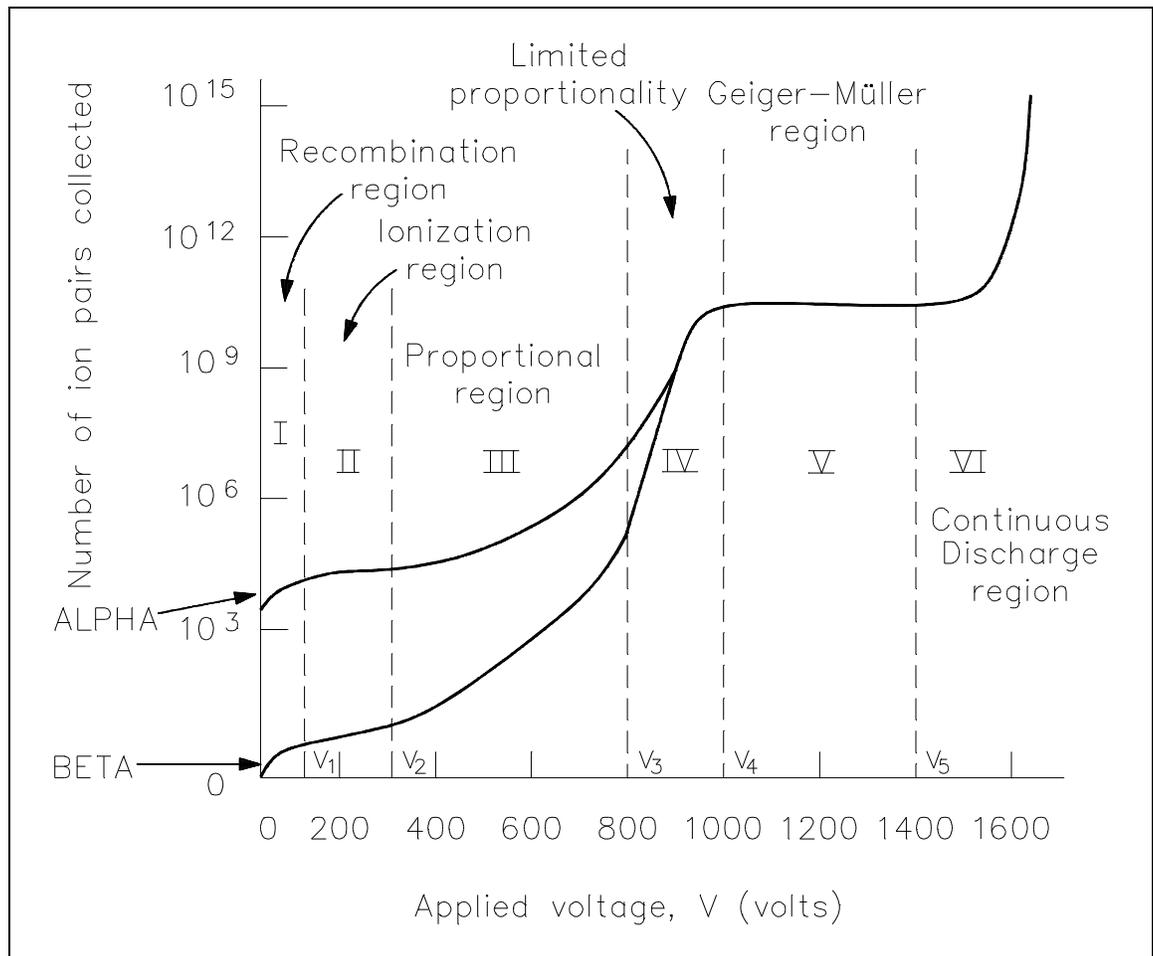


Figure 6 Ion Pairs Collected -vs- Applied Voltage

### Recombination Region

In the recombination region (Region I), as voltage increases to  $V_1$ , the pulse height increases until it reaches a saturation value. At  $V_1$ , the field strength between the cathode and anode is sufficient for collection of all ions produced within the detector. At voltages less than  $V_1$ , ions move slowly toward the electrodes, and the ions tend to recombine to form neutral atoms or molecules. In this case, the pulse height is less than it would have been if all the ions originally formed reached the electrodes. Gas ionization instruments are, therefore, not operated in this region of response.

## **Ionization Region**

As voltage is increased in the ionization region (Region II), there is no appreciable increase in the pulse height. The field strength is more than adequate to ensure collection of all ions produced; however, it is insufficient to cause any increase in ion pairs due to gas amplification. This region is called the ionization chamber region.

## **Proportional Region**

As voltage increases to the proportional region (Region III), the pulse height increases smoothly. The voltage is sufficient to produce a large potential gradient near the anode, and it imparts a very high velocity to the electrons produced through ionization of the gas by charged radiation particles. The velocity of these electrons is sufficient to cause ionization of other atoms or molecules in the gas. This multiplication of electrons is called gas amplification and is referred to as Townsend avalanche. The gas amplification factor (A) varies from  $10^3$  to  $10^4$ . This region is called the proportional region since the gas amplification factor (A) is proportional to applied voltage.

## **Limited Proportional Region**

In the limited proportional region (Region IV), as voltage increases, additional processes occur leading to increased ionization. The strong field causes increased electron velocity, which results in excited states of higher energies capable of releasing more electrons from the cathode. These events cause the Townsend avalanche to spread along the anode. The positive ions remain near where they were originated and reduce the electric field to a point where further avalanches are impossible. For this reason, Region IV is called the limited proportional region, and it is not used for detector operation.

## **Geiger-Müller Region**

The pulse height in the Geiger-Müller region (Region V) is independent of the type of radiation causing the initial ionizations. The pulse height obtained is on the order of several volts. The field strength is so great that the discharge, once ignited, continues to spread until amplification cannot occur, due to a dense positive ion sheath surrounding the central wire (anode).  $V_4$  is termed the threshold voltage. This is where the number of ion pairs level off and remain relatively independent of the applied voltage. This leveling off is called the Geiger plateau which extends over a region of 200 to 300 volts. The threshold is normally about 1000 volts. In the G-M region, the gas amplification factor (A) depends on the specific ionization of the radiation to be detected.

### **Continuous Discharge Region**

In the continuous discharge region (Region VI), a steady discharge current flows. The applied voltage is so high that, once ionization takes place in the gas, there is a continuous discharge of electricity, so that the detector cannot be used for radiation detection.

Radiation detectors are normally designed to respond to a certain type of radiation. Since the detector response can be sensitive to both energy and intensity of the radiation, each type of detector has defined operating limits based on the characteristics of the radiation to be measured. A large variety of detectors are in use in DOE facilities to detect alpha and beta particles, gamma rays, or neutrons. Some types of detectors are capable of distinguishing between the types of radiation; others are not. Some detectors only count the number of particles that enter the detector, while others are used to determine both the number and energy of the incident particles. Most detectors used in DOE facilities have one thing in common: they respond only to electrons produced in the detector. In order to detect the different types of incident particles, the particle's energy must be converted to electrons in the detector.

Gas-filled detectors are used, for the most part, to measure alpha and beta particles, neutrons, and gamma rays. The detectors operate in the ionization, proportional, and G-M regions with an arrangement most sensitive to the type of radiation being measured. Neutron detectors utilize ionization chambers or proportional counters of appropriate design. Compensated ion chambers,  $\text{BF}_3$  counters, fission counters, and proton recoil counters are examples of neutron detectors.

## **Summary**

The alpha curve is higher than the beta curve from Region I to part of Region IV due to the larger number of ion pairs produced by the initial reaction of the incident radiation. Detector voltage principles are summarized below.

### **Gas Amplification Region Summary**

#### Recombination Region

- The voltage is such a low value that recombination takes place before most of the negative ions are collected by the electrode.

#### Ionization Region

- The voltage is sufficient to ensure all ion pairs produced by the incident radiation are collected.
- No gas amplification takes place.

#### Proportional Region

- The voltage is sufficient to ensure all ion pairs produced by the incident radiation are collected.
- Amount of gas amplification is proportional to the applied voltage.

#### Limited Proportional Region

- As voltage increases, additional processes occur leading to increased ionizations.
- Since positive ions remain near their point of origin, further avalanches are impossible.

#### Geiger-Müller Region

- The ion pair production is independent of the radiation, causing the initial ionization.
- The field strength is so great that the discharge continues to spread until amplification cannot occur, due to a dense positive ion sheath surrounding the central wire.

#### Continuous Discharge Region

- The applied voltage is so high that, once ionization takes place, there is a continuous discharge of electricity.

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## PROPORTIONAL COUNTER

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*A proportional counter is a detector that operates in the proportional region.*

- EO 2.1**      **DESCRIBE** the operation of a proportional counter to include:
- a.      **Radiation detection**
  - b.      **Quenching**
  - c.      **Voltage variations**

---

A proportional counter is a detector which operates in the proportional region, as shown in Figure 6. Figure 7 illustrates a simplified proportional counter circuit.

To be able to detect a single particle, the number of ions produced must be increased. As voltage is increased into the proportional region, the primary ions acquire enough energy to cause secondary ionizations (gas amplification) and increase the charge collected. These secondary ionizations may cause further ionization.

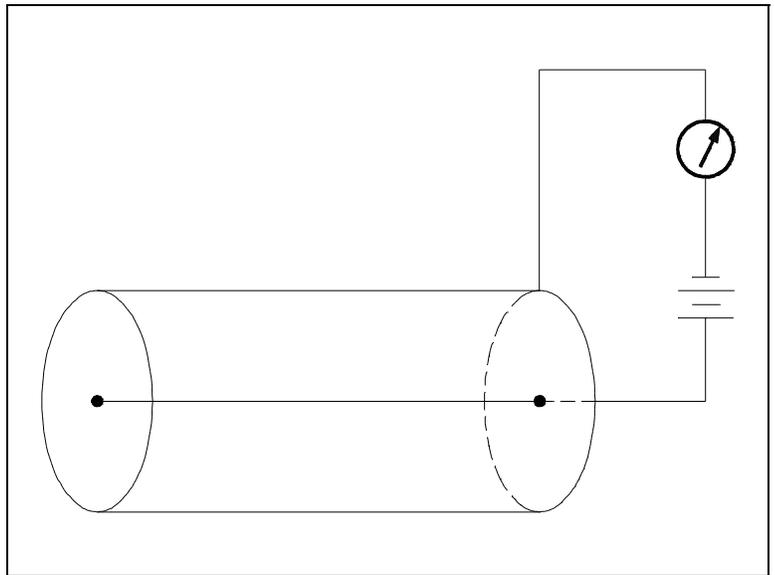


Figure 7 Proportional Counter

In this region, there is a linear relationship between the number of ion pairs collected and applied voltage. A charge amplification of  $10^4$  can be obtained in the proportional region. By proper functional arrangements, modifications, and biasing, the proportional counter can be used to detect alpha, beta, gamma, or neutron radiation in mixed radiation fields.

To a limited degree, the fill-gas will determine what type of radiation the proportional counter will be able to detect. Argon and helium are the most frequently used fill gases and allow for the detection of alpha, beta, and gamma radiation. When detection of neutrons is necessary, the detectors are usually filled with boron-trifluoride gas.

The simplified circuit, illustrated in Figure 7, shows that the detector wall acts as one electrode, while the other electrode is a fine wire in the center of the chamber with a positive voltage applied.

Figure 8 illustrates how the number of electrons collected varies with the applied voltage.

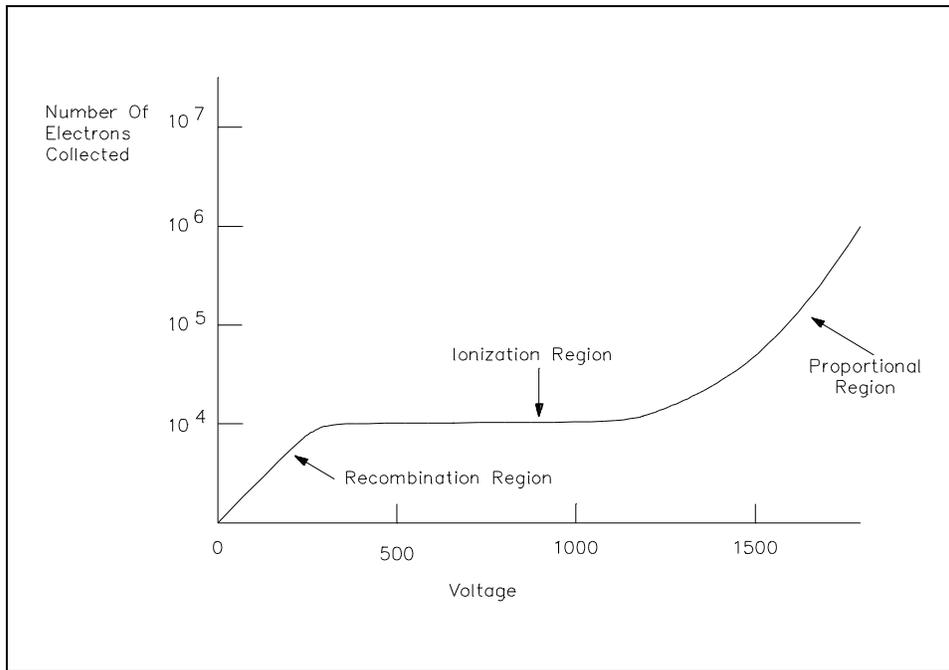


Figure 8 Gas Ionization Curve

When a single gamma ray interacts with the gas in the chamber, it produces a rapidly moving electron which produces secondary electrons. About 10,000 electrons may be formed depending on the gas used in the chamber. The applied voltage can be increased until the amount of recombination is very low. However, further increases do not appreciably increase the number of electrons collected. This region in which all 10,000 electrons are collected is the ionization region.

As applied voltage is increased above 1000 V, the number of electrons becomes greater than the initial 10,000. The additional electrons which are collected are due to gas amplification. As voltage is increased, the velocity of the 10,000 electrons produced increases. However, beyond a certain voltage, the 10,000 electrons are accelerated to such speeds that they have enough energy to cause more ionization. This phenomenon is called gas amplification.

As an example, if the 10,000 electrons produced by the gamma ray are increased to 40,000 by gas amplification, the amplification factor would be 4. Gas amplification factors can range from unity in the ionization region to  $10^3$  or  $10^4$  in the proportional region. The high amplification factor of the proportional counter is the major advantage over the ionization chamber. The internal amplification of the proportional counter is such that low energy particles ( $< 10$  KeV) can be registered, whereas the ion chamber is limited by amplifier noise to particles of  $> 10$  KeV energy.

Proportional counters are extremely sensitive, and the voltages are large enough so that all of the electrons are collected within a few tenths of a microsecond. Each pulse corresponds to one gamma ray or neutron interaction. The amount of charge in each pulse is proportional to the number of original electrons produced. The proportionality factor in this case is the gas amplification factor. The number of electrons produced is proportional to the energy of the incident particle.

For each electron collected in the chamber, there is a positively charged gas ion left over. These gas ions are heavy compared to an electron and move much more slowly. Eventually the positive ions move away from the positively charged central wire to the negatively charged wall and are neutralized by gaining an electron. In the process, some energy is given off, which causes additional ionization of the gas atoms. The electrons produced by this ionization move toward the central wire and are multiplied en route. This pulse of charge is unrelated to the radiation to be detected and can set off a series of pulses. These pulses must be eliminated or "quenched."

One method for quenching these discharges is to add a small amount ( $\approx 10\%$ ) of an organic gas, such as methane, in the chamber. The quenching gas molecules have a weaker affinity for electrons than the chamber gas does; therefore, the ionized atoms of the chamber gas readily take electrons from the quenching gas molecules. Thus, the ionized molecules of quenching gas reach the chamber wall instead of the chamber gas. The ionized molecules of the quenching gas are neutralized by gaining an electron, and the energy liberated does not cause further ionization, but causes dissociation of the molecule. This dissociation quenches multiple discharges. The quenching gas molecules are eventually consumed, thus limiting the lifetime of the proportional counter. There are, however, some proportional counters that have an indefinite lifetime because the quenching gas is constantly replenished. These counters are referred to as gas flow counters.

## **Summary**

Proportional counters are summarized below.

### **Proportional Counters Summary**

- When radiation enters a proportional counter, the detector gas, at the point of incident radiation, becomes ionized.
- The detector voltage is set so that the electrons cause secondary ionizations as they accelerate toward the electrode.
- The electrons produced from the secondary ionizations cause additional ionizations.
- This multiplication of electrons is called gas amplification.
- Varying the detector voltage within the proportional region increases or decreases the gas amplification factor.
- A quenching gas is added to give up electrons to the chamber gas so that inaccuracies are NOT introduced due to ionizations caused by the positive ion.

## PROPORTIONAL COUNTER CIRCUITRY

*Proportional counters measure different types of radiation.*

- EO 2.2**      **Given a block diagram of a proportional counter circuit, STATE the purpose of the following major blocks:**
- a.      Proportional counter**
  - b.      Preamplifier/amplifier**
  - c.      Single channel analyzer/discriminator**
  - d.      Scaler**
  - e.      Timer**

Proportional counters measure the charge produced by each particle of radiation. To make full use of the counter's capabilities, it is necessary to measure the number of pulses and the charge in each pulse. Figure 9 shows a typical circuit used to make such measurements.

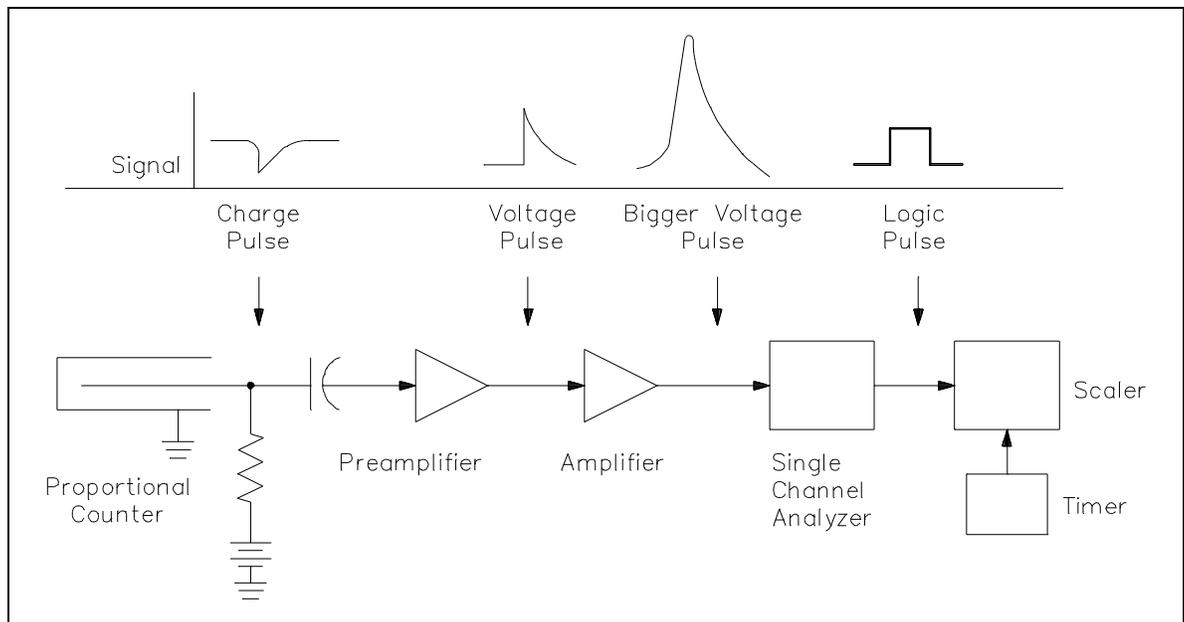


Figure 9 Proportional Counter Circuit

The capacitor converts the charge pulse to a voltage pulse. The voltage is equal to the amount of charge divided by the capacitance of the capacitor, as given in Equation 6-8.

$$V = \frac{Q}{C} \tag{6-8}$$

where

V = voltage pulse (volts)

Q = charge (coulombs)

C = capacitance (farads)

The preamplifier amplifies the voltage pulse. Further amplification is obtained by sending the signal through an amplifier circuit (typically about 10 volts maximum). The pulse size is then determined by a single channel analyzer. Figure 10 shows the operation of a single channel analyzer.

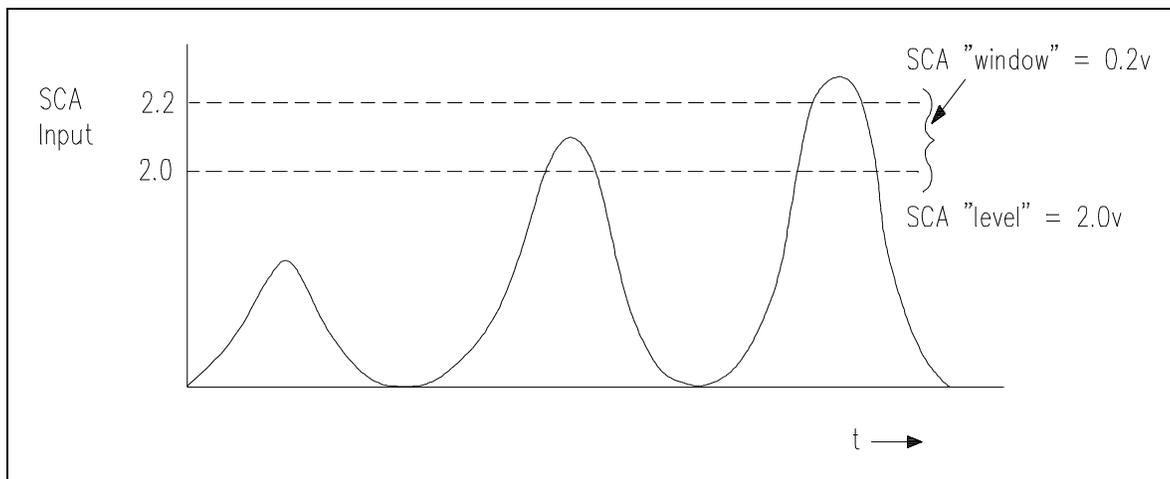


Figure 10 Single Channel Analyzer Operation

The single channel analyzer has two dial settings: a LEVEL dial and a WINDOW dial. For example, when the level is set at 2 volts, and the window at 0.2 volts, the analyzer will give an output pulse only when the input pulse is between 2 and 2.2 volts. The output pulse is usually a standardized height and width logic pulse, as shown in Figure 11.

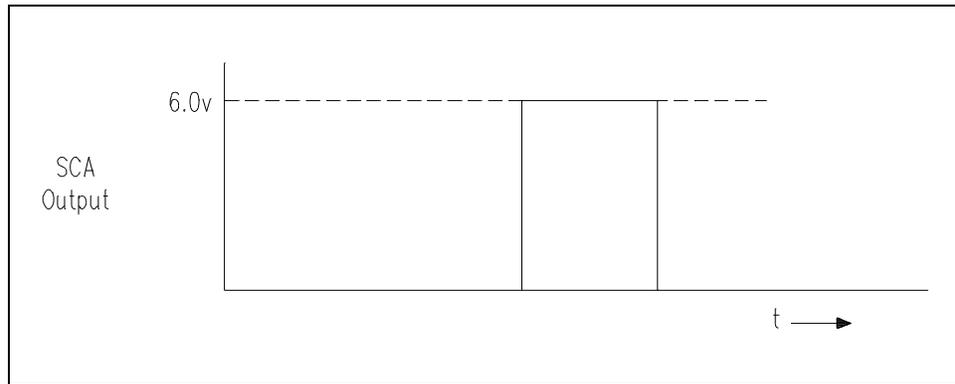


Figure 11 Single Channel Analyzer Output

Since the single channel analyzer can be set so that an output is only produced by a certain pulse size, it provides for the counting of one specific radiation in a mixed radiation field.

This output is fed to a scaler which counts the number of pulses it receives. A timer gates the scaler so that the scaler counts the pulses for a predetermined length of time. Knowing the number of counts per a given time interval allows calculation of the count rate (number of counts per unit time).

Proportional counters can also count neutrons by introducing boron into the chamber. The most common means of introducing boron is by combining it with tri-fluoride gas to form Boron Tri-Fluoride ( $\text{BF}_3$ ). When a neutron interacts with a boron atom, an alpha particle is emitted. The  $\text{BF}_3$  counter can be made sensitive to neutrons and not to gamma rays.

Gamma rays can be eliminated because the neutron-induced alpha particles produce more ionizations than gamma rays produce. This is due mainly to the fact that gamma ray-induced electrons have a much longer range than the dimensions of the chamber; the alpha particle energy is, in most cases, greater than gamma rays produced in a reactor. Therefore, neutron pulses are much larger than gamma ray-produced pulses.

By using a discriminator, the scaler can be set to read only the larger pulses produced by the neutron. A discriminator is basically a single channel analyzer with only one setting. Figure 12 illustrates the operation of a discriminator.

If the discriminator is set at 2 volts, then any input pulse  $\geq 2$  volts causes an output pulse.

Figure 13 shows a typical circuit used to measure neutrons with a  $BF_3$  proportional counter.

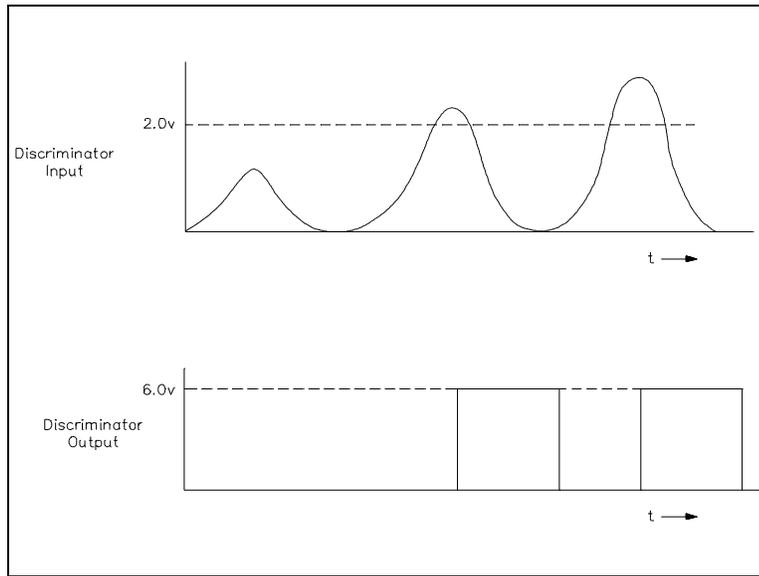


Figure 12 Discriminator

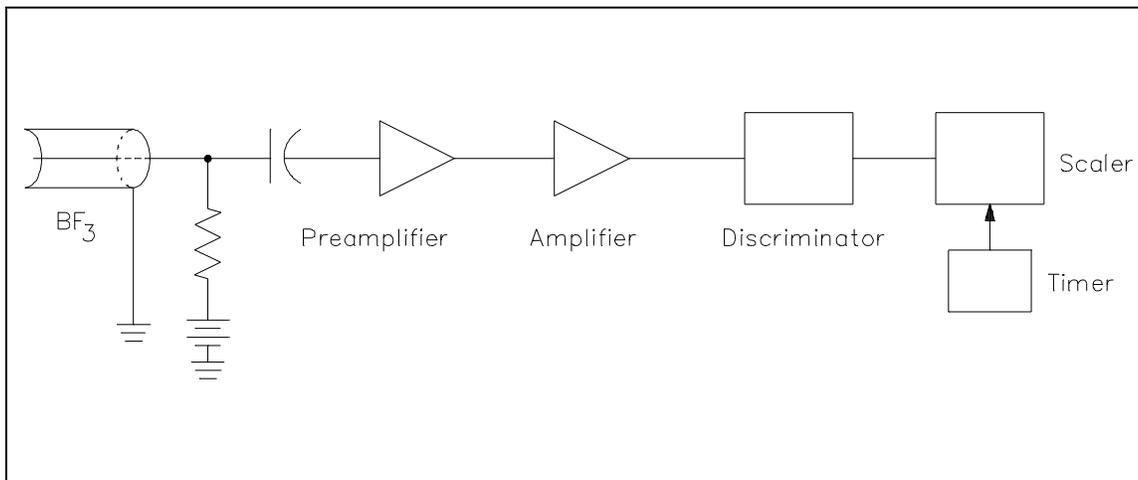


Figure 13  $BF_3$  Proportional Counter Circuit

The  $\text{BF}_3$  proportional counter is used to monitor low power levels in a nuclear reactor. It is used in the "startup" or "source range" channels. Proportional counters cannot be used at high power levels because they are pulse-type detectors. Typically, it takes 10 to 20 microseconds for each pulse to go from 10% of its peak, to its peak, and back to 10%. If another neutron interacts in the chamber during this time, the two pulses are superimposed. The voltage output would never drop to zero between the two pulses, and the chamber would draw a steady current as electrons are being produced.

### **Summary**

Proportional counter circuitry is summarized below.

#### **Proportional Counter Circuitry Summary**

- The proportional counter measures the charge produced by each particle of radiation.
- The preamplifier/amplifier amplifies the voltage pulse to a usable size.
- The single channel analyzer/discriminator produces an output only when the input is a certain pulse size.
- The scaler counts the number of pulses received during a predetermined length of time.
- The timer provides the gating signal to the scaler.

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## IONIZATION CHAMBER

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*The ionization chamber is a detector that operates in the ionization region.*

- EO 2.3**      **DESCRIBE the operation of an ionization chamber to include:**
- a.      Radiation detection**
  - b.      Voltage variations**
  - c.      Gamma sensitivity reduction**
- 

Ionization chambers are electrical devices that detect radiation when the voltage is adjusted so that the conditions correspond to the ionization region (refer to Region II of Figure 6). The charge obtained is the result of collecting the ions produced by radiation. This charge will depend on the type of radiation being detected. Ionization chambers have two distinct disadvantages when compared to proportional counters: they are less sensitive, and they have a slower response time.

There are two types of ionization chambers to be discussed: the pulse counting ionization chamber and the integrating ionization chamber. In the pulse counting ionization chamber, the pulses are detected due to particles traversing the chamber. In the integrating chamber, the pulses add, and the integrated total of the ionizations produced in a predetermined period of time is measured. The same type of ionization chamber may be used for either function. However, as a general rule, the integrating type ionization chamber is used.

Flat plates or concentric cylinders may be utilized in the construction of an ionization chamber. The flat plate design is preferred because it has a well-defined active volume and ensures that ions will not collect on the insulators and cause a distortion of the electric field. The concentric cylinder design does not have a well-defined active volume because of the variation in the electric field as the insulator is approached. Ionization chamber construction differs from the proportional counter (flat plates or concentric cylinders vice a cylinder and central electrode) to allow for the integration of pulses produced by the incident radiation. The proportional counter would require such exact control of the electric field between the electrodes that it would not be practical.

Figure 14 illustrates a simple ionization circuit consisting of two parallel plates of metal with an air space between them. The plates are connected to a battery which is connected in series with a highly sensitive ammeter.

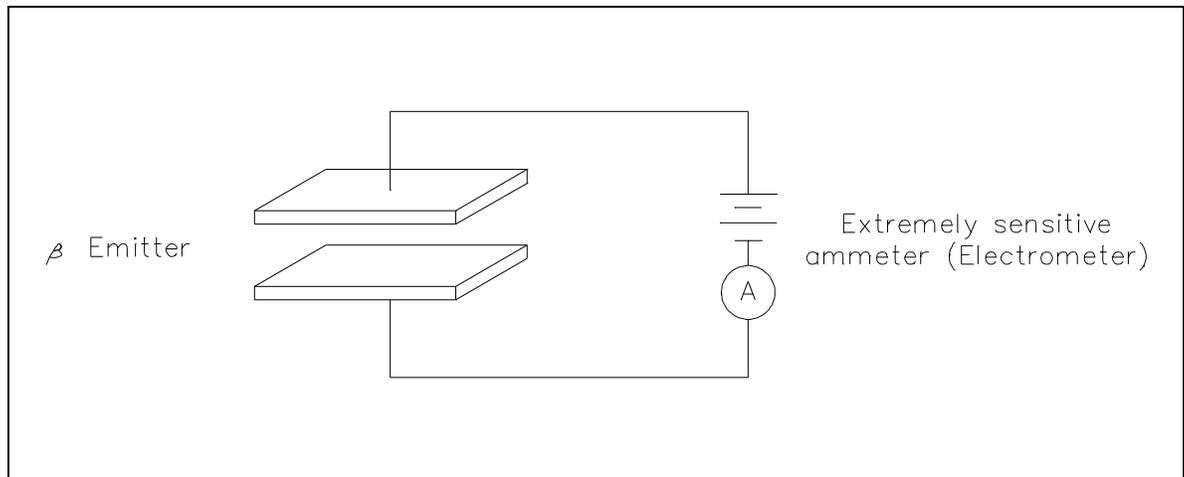


Figure 14 Simple Ionization Circuit

If a radioactive source that is an emitter of beta particles is placed near the detector, the beta particles will pass between the plates and strike atoms in the air. With sufficient energy, the beta particle causes an electron to be ejected from an atom in air. A single beta particle may eject 40 to 50 electrons for each centimeter of path length traveled. The electrons ejected by the beta particle often have enough energy to eject more electrons from other atoms in air. The total number of electrons produced is dependent on the energy of the beta particle and the gas between the plates of the ionization chamber.

In general, a 1 MeV beta particle will eject approximately 50 electrons per centimeter of travel, while a 0.05 MeV beta particle will eject approximately 300 electrons. The lower energy beta ejects more electrons because it has more collisions. Each electron produced by the beta particle, while traveling through air, will produce thousands of electrons. A current of 1 micro-ampere consists of about  $10^{12}$  electrons per second.

If 1 volt is applied to the plates of the ionization chamber shown in Figure 14, some of the free electrons will be attracted to the positive plate of the detector. This attraction is not strong because 1 volt does not create a strong electric field between the two plates. The free electrons will tend to drift toward the positive plate, causing a current to flow, which is indicated on the ammeter. Not all of the free electrons will make it to the positive plate because the positively charged atoms that resulted when an electron was ejected may recapture other free electrons. Therefore, the ammeter will register only a fraction of the number of free electrons between the plates.

When the voltage is increased, the free electrons are more strongly attracted to the positive plate. They will move toward the positive plate more quickly and will have less opportunity to recombine with the positive ions. Figure 15 shows a plot of the number of electrons measured by the ammeter as a function of applied voltage.

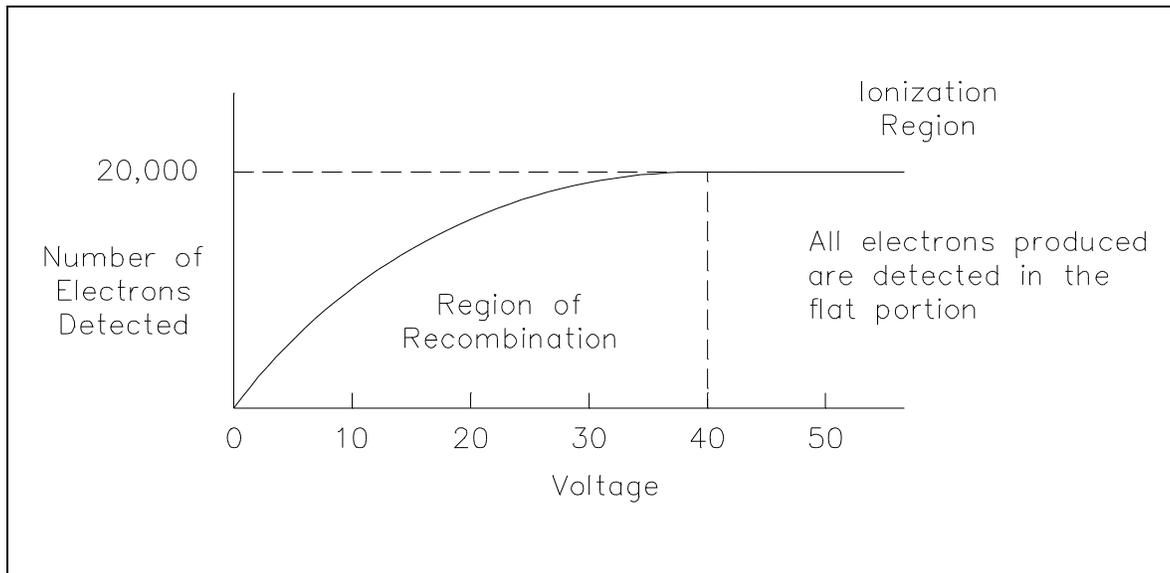


Figure 15 Recombination and Ionization Regions

At zero voltage, no attraction of electrons between the plates occurs. The electrons will eventually recombine, so there is no current flow. As the applied voltage is increased, the positive plate will begin to attract free electrons more strongly, and a higher percentage will reach the positive plate. As the voltage is increased further, a point will be reached in which all of the electrons produced in the chamber will reach the positive plate. Any further increase in voltage has no effect on the number of electrons collected.

The simple ionization chamber shown in Figure 14 can also be utilized for the detection of gamma rays. Since the ammeter is sensitive only to electrons, gamma rays must interact with the atoms in air between the plates to release electrons. The gamma rays interact by Compton scattering, photoelectric effect, or pair production. Each of these interactions causes some, or all, of the energy of the incident gamma rays to be converted into the kinetic energy of the ejected electrons. The ejected electrons move at very high speeds and cause other electrons to be ejected from their atoms. All of these electrons can be collected by the positively charged plate and measured by the ammeter.

The plates in an ionization chamber are normally enclosed in metal, as shown by Figure 16.

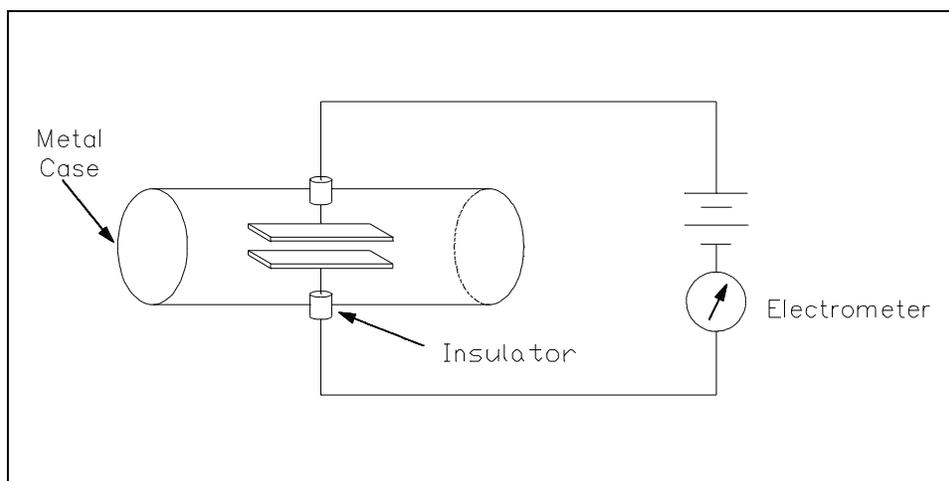
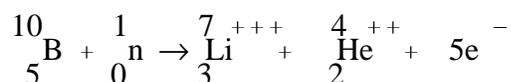


Figure 16 Ionization Chamber

This metal chamber serves to shield the plates from outside electric fields and to contain the air or other gas. Gamma rays have very little trouble in penetrating the metal walls of the chamber. Beta particles and alpha particles, however, are stopped by the metal wall. For alpha and beta particles to be detected, some means must be provided for a thin wall or "window." This window must be thin enough for the alpha and beta particles to penetrate. However, a window of almost any thickness will prevent an alpha particle from entering the chamber.

Neutrons can also be detected by an ionization chamber. As we already know, neutrons are uncharged; therefore, they cause no ionizations themselves. If the inner surface of the ionization chamber is coated with a thin coat of boron, the following reaction can take place.



A neutron is captured by a boron atom, and an energetic alpha particle is emitted. The alpha particle causes ionization within the chamber, and ejected electrons cause further secondary ionizations.

Another method for detecting neutrons using an ionization chamber is to use the gas boron trifluoride ( $\text{BF}_3$ ) instead of air in the chamber. The incoming neutrons produce alpha particles when they react with the boron atoms in the detector gas. Either method may be used to detect neutrons in nuclear reactor neutron detectors.

When using an ionization chamber for detecting neutrons, beta particles can be prevented from entering the chamber by walls thick enough to shield out all of the beta particles. Gamma rays cannot be shielded from the detector; therefore, they always contribute to the total current read by the ammeter. This effect is not desired because the detector responds not only to neutrons, but also to gamma rays. Several ways are available to minimize this problem.

Discrimination is possible because the ionizations produced by the alpha particles differ in energy levels from those produced by gamma rays. A 1 MeV alpha particle moving through the gas loses all of its energy in a few centimeters. Therefore, all of the secondary electrons are produced along a path of only a few centimeters. A 1 MeV gamma ray produces a 1 MeV electron, and this electron has a long range and loses its energy over the entire length of its range. If we make the sensitive volume of the chamber smaller without reducing the area of the coated boron, the sensitivity to gamma rays is reduced.

Figure 17 illustrates how the chamber may be modified to accomplish this reduction.

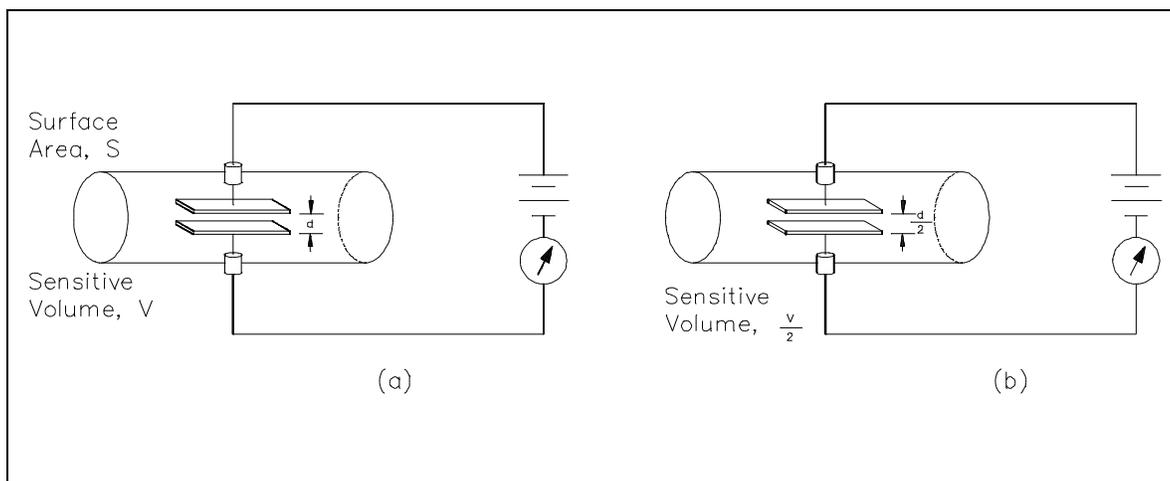


Figure 17 Minimizing Gamma Influence by Size and Volume

In Figure 17(b) there is half as much gas in the sensitive volume as in the chamber in Figure 17(a). As a result, gamma rays have only half as much gas to interact with; therefore, half the number of electrons are produced. The area which is boron-coated has not changed, and both chambers produce the same number of neutron-induced alpha particles. Also, the gamma ray-induced electrons produce fewer ionizations because the range of these electrons is longer than the dimensions of the sensitive volume. The range of neutron-induced alpha particles is short, and all of the energy will be dissipated within the sensitive volume, even when the volume is smaller.

Gamma interference can also be minimized by reducing the pressure of the gas inside the chamber. The reduction in pressure reduces the number of atoms within the sensitive volume and has the same effect as reducing the volume.

Ionization chamber sensitivity to gamma rays can also be reduced by increasing chamber sensitivity to neutrons. This is accomplished by increasing the boron-coated area, as shown in Figure 18. Both ionization chambers shown in Figure 18 have the same sensitive volume.

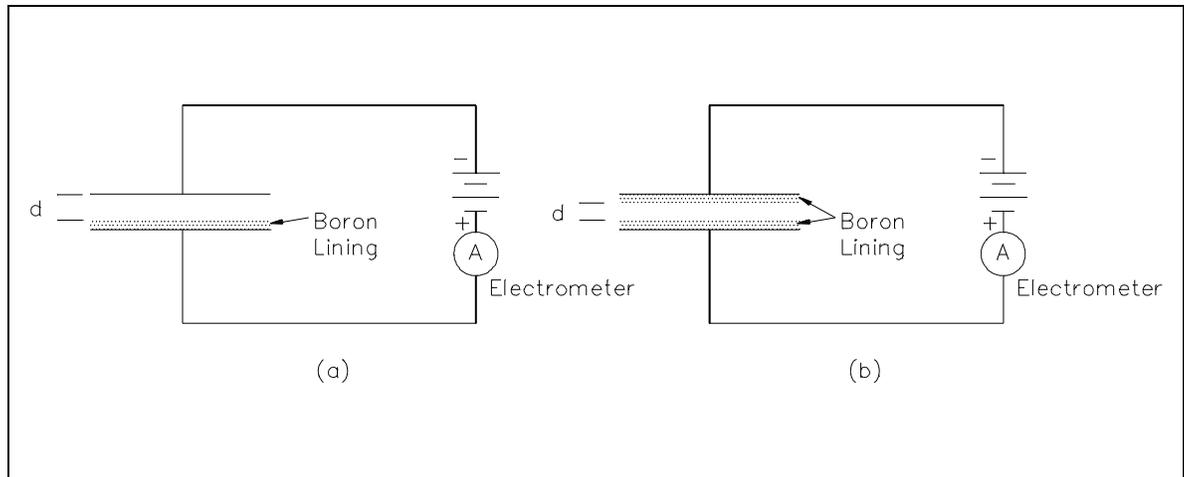


Figure 18 Minimizing Gamma Influence with Boron Coating Area

The ionization chamber in Figure 18(b) has twice the boron area as the ionization chamber in Figure 18(a). The result is that more neutron-induced alpha particles are produced, and neutron sensitivity is increased. Ionization chambers supplied commercially are designed to minimize gamma sensitivity by both of the techniques described previously. Gamma sensitivity can be minimized but not eliminated. For reactors operating near peak power, neutrons are the dominant radiation, and almost all of the current is due to neutrons. These chambers are used at high reactor powers and are referred to as uncompensated ion chambers. The uncompensated ion chamber is not suitable for use at intermediate or low power levels because the gamma response at these power levels can be significant compared to the neutron response.

## **Summary**

Ionization chambers are summarized below.

### **Ionization Chamber Summary**

- When radiation enters an ionization chamber, the detector gas at the point of incident radiation becomes ionized.
- Some of the electrons have sufficient energy to cause additional ionizations.
- The electrons are attracted to the electrode by the voltage potential set up on the detector.
- If the voltage is set high enough, all of the electrons will reach the electrode before recombination takes place.
- Gamma sensitivity reduction is accomplished by either reducing the amount of chamber gas or increasing the boron coated surface area.

## COMPENSATED ION CHAMBER

*Gamma compensation is required at intermediate reactor power levels to ensure accurate power reading.*

### EO 2.4 DESCRIBE how a compensated ion chamber compensates for gamma radiation.

Compensating for the response to gamma rays extends the useful range of the ionization chamber. Compensated ionization chambers consist of two separate chambers; one chamber is coated with boron, and one chamber is not. The coated chamber is sensitive to both gamma rays and neutrons, while the uncoated chamber is sensitive only to gamma rays. Instead of having two separate ammeters and subtracting the currents, the subtraction of these currents is done electrically, and the net output of both detectors is read on a single ammeter. If the polarities are arranged so that the two chambers' currents oppose one another, the reading obtained from the ammeter indicates the difference between the two currents. One plate of the compensated ion chamber is common to both chambers; one side is coated with boron, while the other side is not.

Figure 19 shows the basic circuitry for a compensated ion chamber.

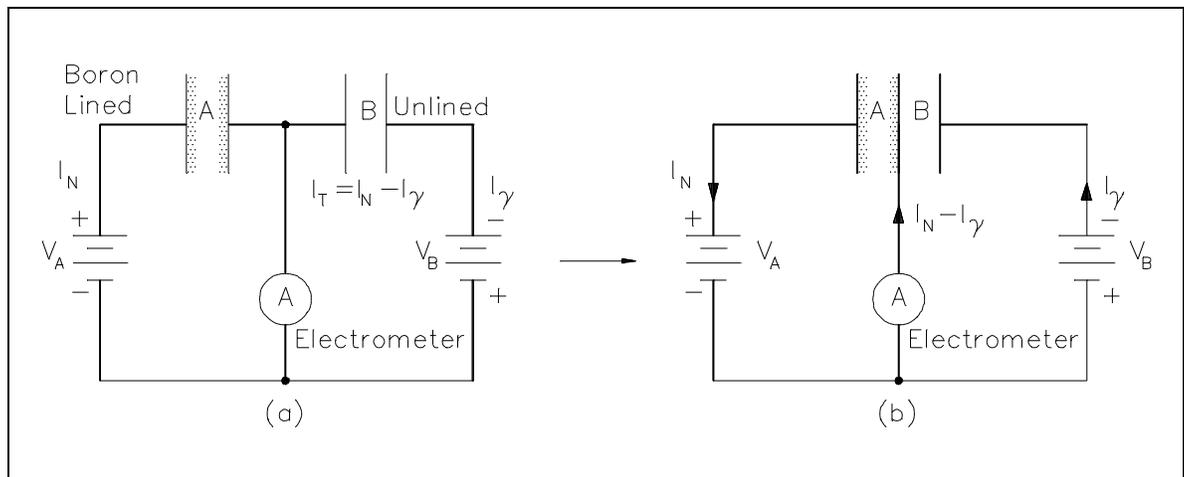


Figure 19 Compensated Ion Chamber

The boron coated chamber is referred to as the working chamber; the uncoated chamber is called the compensating chamber. When exposed to a gamma source, the battery for the working chamber will set up a current flow that deflects the meter in one direction. The compensating chamber battery will set up a current flow that deflects the meter in the opposite direction. If both chambers are identical, and both batteries are of the same voltage, the net current flow is exactly zero. Therefore, the compensating chamber cancels the current due to gamma rays.

The two chambers of a compensated ion chamber are never truly identical; in fact, they are often purposely constructed in different shapes. The chambers are normally constructed as concentric cylinders, as illustrated in Figure 20.

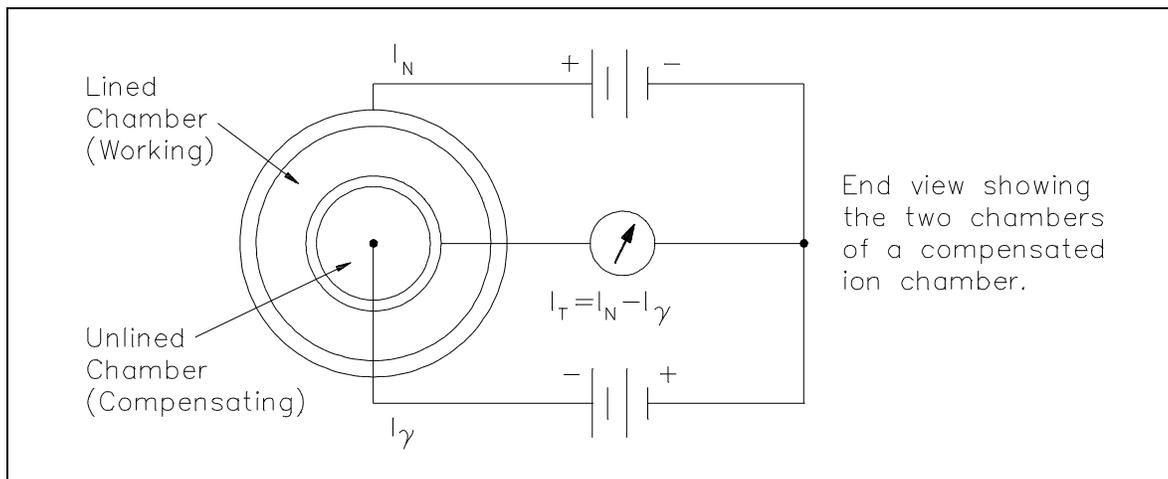


Figure 20 Compensated Ion Chamber with Concentric Cylinders

The use of concentric cylinders has an advantage because both chambers are exposed to nearly the same radiation field. Even though the chambers are not identical, proper selection of the operating voltage eliminates the gamma current. Working chamber operating voltage is given by the manufacturer and is selected to cause operation on the flat portion of the response curve, where very little recombination occurs. If working chamber voltage is increased to operating voltage, and compensating voltage is left at zero, the measured current will be due to gammas only in the working chamber. For this reason, compensating voltage is set while the reactor is shutdown (a minimum number of neutrons are present).

As the compensating chamber voltage is raised, the measured current will decrease as more of the current from the working chamber is canceled by the current from the compensating chamber. Eventually, the voltage becomes large enough so that the two currents cancel. When the currents cancel, the chamber is said to be 100% compensated, and the measured current is zero. At 100% compensation, the detector will respond to neutrons alone.

The compensating chamber usually has a slightly larger sensitive volume than the working chamber. Increasing the compensating current to a value greater than the working chamber current results in a net negative current. In this condition, the chamber is said to be overcompensated. The compensating chamber cancels too much current from the working chamber, and the meter reads low. In this case, the compensating chamber cancels out all of the gamma current and some of the neutron current.

Percent compensation of a compensated ion chamber gives the percentage of the gamma rays which are canceled out. Percent compensation may be calculated based on measured current, when the detector is exposed to gamma rays only as given in Equation 6-9.

$$\text{Percent Compensation} = 1 - \frac{I_{\text{measured}}}{I_{\text{operating}}} \times 100\% \quad (6-9)$$

where

$I_{\text{measured}}$  = measured current (milliamps)

$I_{\text{operating}}$  = measured current with compensating voltage OFF (milliamps)

If measured current is zero, then percent compensation is 100%. If measured current is positive, the percent compensation is less than 100%, and the chamber is undercompensated. If the measured current is negative, the percent compensation is greater than 100%, and the chamber is overcompensated.

The ionization chamber compensation curve, Figure 21, is a plot of the percent compensation versus compensating voltage. This compensation curve must be plotted prior to using a compensated ion chamber.

In ideal situations, compensated ion chambers operate at 100% compensation, and indicated current is due to neutrons. Small changes in compensating voltage change the percent compensation.

The consequences of operating with an overcompensated or undercompensated chamber are important. The purpose of nuclear instrumentation is to detect and measure neutron level, which is the direct measure of core power. If the compensating voltage is set too high, or overcompensated, some neutron current, as well as all of the gamma current, is blocked, and indicated power is lower than actual core power. If compensating voltage is set too low, or undercompensated, not all of the gamma current is blocked, and indicated power is higher than actual core power. At high power, gamma flux is relatively small compared to neutron flux, and the effects of improper compensation may not be noticed. It is extremely important, however, that the chamber be properly compensated during reactor startup and shutdown.

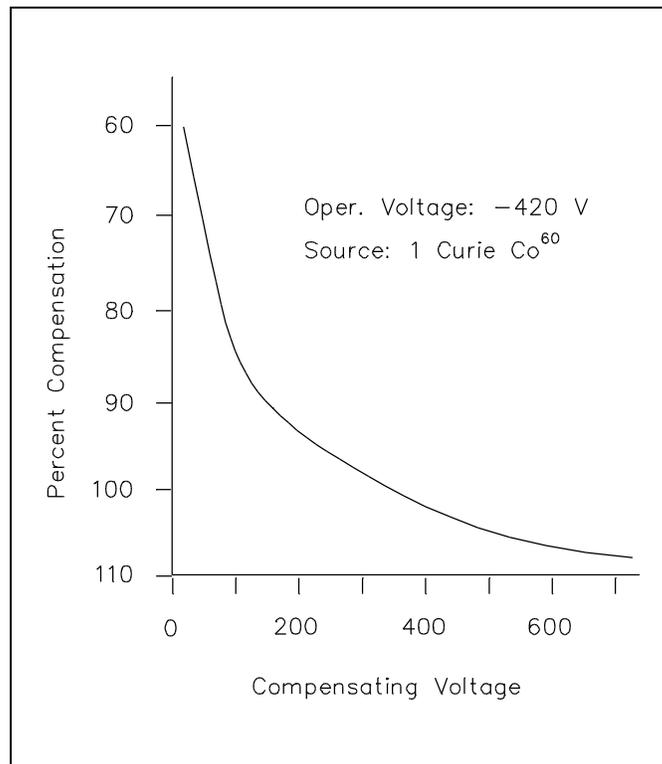


Figure 21 Typical Compensation Curve

## **Summary**

Compensated ion chambers are summarized below.

### **Compensated Ion Chamber Summary**

- A compensated ion chamber has two concentric cylinders: a boron-coated chamber and an uncoated chamber.
- Both gammas and neutrons interact in the boron-coated chamber.
- Only gammas interact in the uncoated chamber.
- The voltages to each chamber are set so that the current from the gammas in the boron-coated chamber cancels the current from the gammas in the uncoated chamber.

## ELECTROSCOPE IONIZATION CHAMBER

*The gold-leaf electroscope has been widely used in the past to study ionizing radiation.*

### EO 2.5 DESCRIBE the operation of an electroscope ionization chamber.

The gold-leaf electroscope has been widely used in the past to study ionizing radiation. The first measurement of the properties of ionizing radiation was accomplished with this instrument. A microscope containing a graduated scale in the eyepiece is used to observe the gold leaf.

The newest electroscope utilizes a quartz fiber and has many advantages over the gold-leaf type. It is portable, less dependent on position, much smaller in size, and more sensitive. The capacity of the quartz fiber electroscope is about 0.2 pico-farads, and its voltage sensitivity is about one volt per division on the scale. The sensitive element is a fine gold plated quartz fiber mounted on a parallel metal support. Figure 22 illustrates a quartz fiber electroscope.

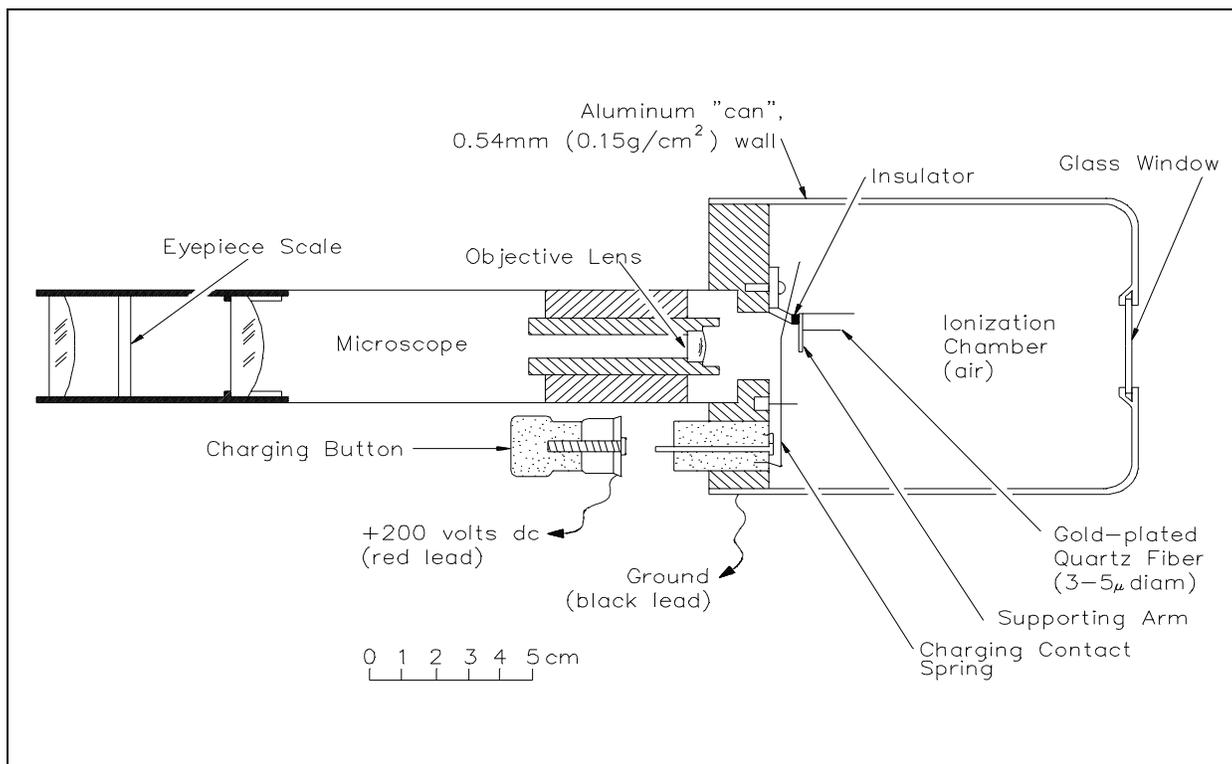


Figure 22 Quartz Fiber Electroscope

A small piece of quartz fiber is mounted across the end of the gold-plated quartz fiber and serves as an index that is viewed through a microscope equipped with an eyepiece scale. The quartz fiber is charged by a battery pressing the charging key. As the quartz fiber is being charged, it is deflected from the support. It takes approximately 200 volts to produce full-scale deflection of the fiber. A glass window at the end of the ionization chamber allows for exposure of the fiber. As the gas (air) is ionized by the incident radiation, the fiber moves toward the position of zero charge. Due to the electroscopes' dependability, simplicity, accuracy, and sensitivity, it is widely used in gamma radiation measurement.

A self-reading pocket dosimeter is an example of an electroscopes ionization chamber. Pocket dosimeters provide personnel with a means of monitoring their radiation exposure. The dosimeters are available in many ranges of gamma exposures from 0 through 200 milliroentgens to 0 through 1000 roentgens. The sensitivity of the instrument is determined at the time of manufacture. Appropriate scale markings are provided with each dose range.

### **Summary**

The operation of an electroscopes ionization chamber is summarized below.

#### **Electroscope Ionization Chamber Summary**

- The electroscopes ionization chamber is charged using a battery.
- Charging causes the quartz fiber to be deflected from the support.
- When radiation ionizes the gas (air) in the chamber, the charge is reduced, and the fiber moves towards the zero charge position.

## GEIGER-MÜLLER DETECTOR

The Geiger-Müller detector is a radiation detector which operates in the G-M region.

**EO 2.6 DESCRIBE the operation of a Geiger-Müller (G-M) detector to include:**

- a. **Radiation detection**
- b. **Quenching**
- c. **Positive ion sheath**

The Geiger-Müller or G-M detector is a radiation detector that operates in Region V, or G-M region, as shown on Figure 23. G-M detectors produce larger pulses than other types of detectors. However, discrimination is not possible, since the pulse height is independent of the type of radiation. Counting systems that use G-M detectors are not as complex as those using ion chambers or proportional counters.

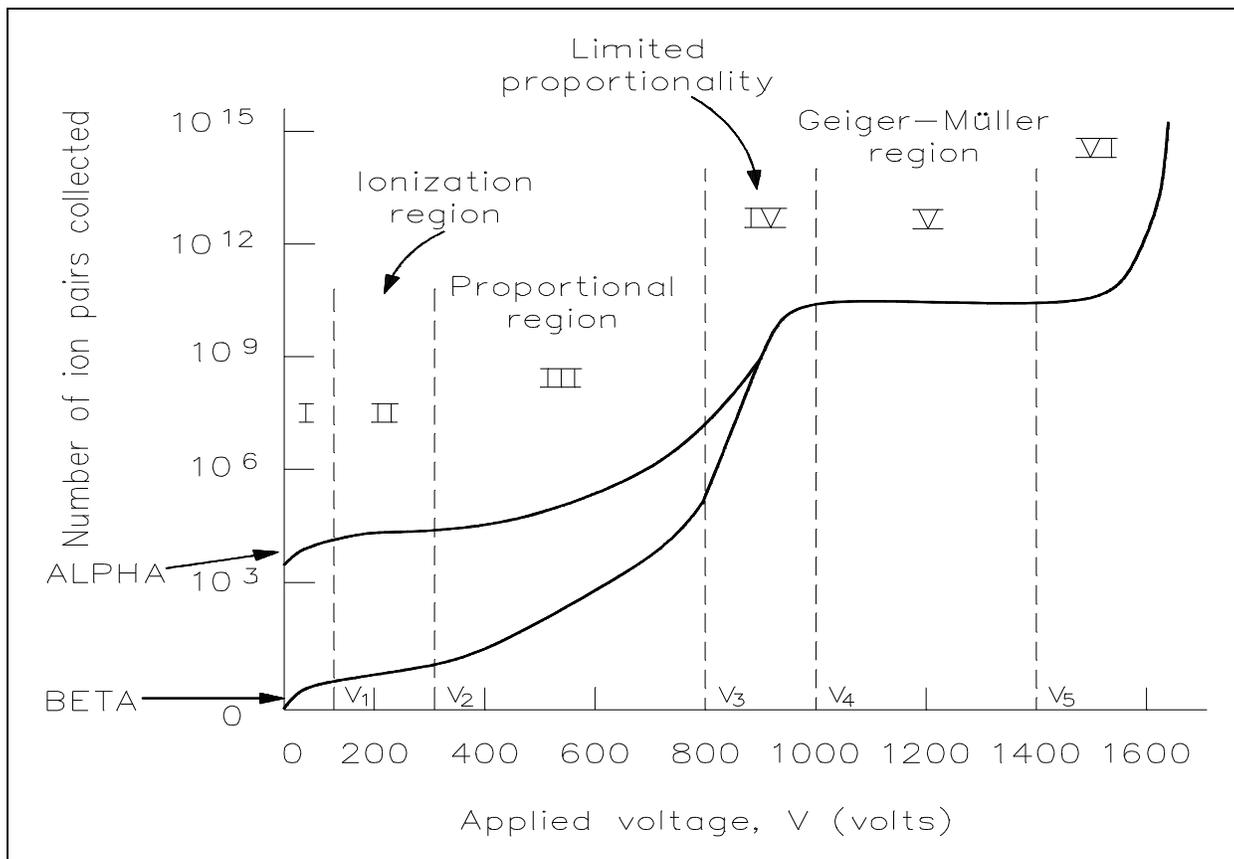


Figure 23 Gas Ionization Curve

The number of electrons collected by a gas-filled detector varies as applied voltage is increased. Once the voltage is increased beyond the proportional region, another flat portion of the curve is reached; this is known as the Geiger-Müller region. The Geiger-Müller region has two important characteristics:

- The number of electrons produced is independent of applied voltage.
- The number of electrons produced is independent of the number of electrons produced by the initial radiation.

This means that the radiation producing one electron will have the same size pulse as radiation producing hundreds or thousands of electrons. The reason for this characteristic is related to the way in which electrons are collected.

When a gamma produces an electron, the electron moves rapidly toward the positively charged central wire. As the electron nears the wire, its velocity increases. At some point its velocity is great enough to cause additional ionizations. As the electrons approach the central wire, the additional ionizations produce a larger number of electrons in the vicinity of the central wire.

As discussed before, for each electron produced there is a positive ion produced. As the applied voltage is increased, the number of positive ions near the central wire increases, and a positively charged cloud (called a positive ion sheath) forms around the central wire. The positive ion sheath reduces the field strength of the central wire and prevents further electrons from reaching the wire. It might appear that a positive ion sheath would increase the effect of the positive central wire, but this is not true; the positive potential is applied to the very thin central wire that makes the strength of the electric field very high. The positive ion sheath makes the central wire appear much thicker and reduces the field strength. This phenomenon is called the detector's space charge. The positive ions will migrate toward the negative chamber picking up electrons. As in a proportional counter, this transfer of electrons can release energy, causing ionization and the liberation of an electron. In order to prevent this secondary pulse, a quenching gas is used, usually an organic compound.

The G-M counter produces many more electrons than does a proportional counter; therefore, it is a much more sensitive device. It is often used in the detection of low-level gamma rays and beta particles for this reason. Electrons produced in a G-M tube are collected very rapidly, usually within a fraction of a microsecond. The output of the G-M detector is a pulse charge and is often large enough to drive a meter without additional amplification. Because the same size pulse is produced regardless of the amount of initial ionization, the G-M counter cannot distinguish radiation of different energies or types. This is the reason G-M counters are not adaptable for use as neutron detectors. The G-M detector is mainly used for portable instrumentation due to its sensitivity, simple counting circuit, and ability to detect low-level radiation.

## **Summary**

The operation of Geiger-Müller detectors are summarized below.

### **G-M Detector Summary**

- The voltage of a Geiger-Müller (G-M) detector is set so that any incident radiation produces the same number of electrons.
- As long as voltage remains in the G-M region, electron production is independent of operating voltage and the initial number of electrons produced by the incident radiation.
- The operation voltage causes a large number of ionizations to occur near the central electrode as the electrons approach.
- The large number of positive ions form a positive ion sheath which prevents additional electrons from reaching the electrode.
- A quenching gas is used in order to prevent a secondary pulse due to ionization by the positive ions.

## SCINTILLATION COUNTER

*The scintillation counter is a solid state radiation detector.*

- EO 2.7 DESCRIBE the operation of a scintillation counter to include:**
- a. Radiation detection**
  - b. Three classes of phosphors**
  - c. Photomultiplier tube operation**

The scintillation counter is a solid state radiation detector which uses a scintillation crystal (phosphor) to detect radiation and produce light pulses. Figure 24 is important in the explanation of scintillation counter operation.

As radiation interacts in the scintillation crystal, energy is transferred to bound electrons of the crystal's atoms. If the energy that is transferred is greater than the ionization energy, the electron enters the conduction band and is free from the binding forces of the parent atom. This leaves a vacancy in the valence band and is termed a hole. If the energy transferred is less than the binding energy, the electron remains attached, but exists in an excited energy state. Once again, a hole is created in the valence band. By adding impurities during the growth of the scintillation crystal, the manufacturer is able to produce activator centers with energy levels located within the forbidden energy gap. The activator center can trap a mobile electron, which raises the activator center from its ground state, G, to an excited state, E. When the center de-excites, a photon is emitted. The activator centers in a scintillation crystal are referred to as luminescence centers. The emitted photons are in the visible region of the electromagnetic spectrum.

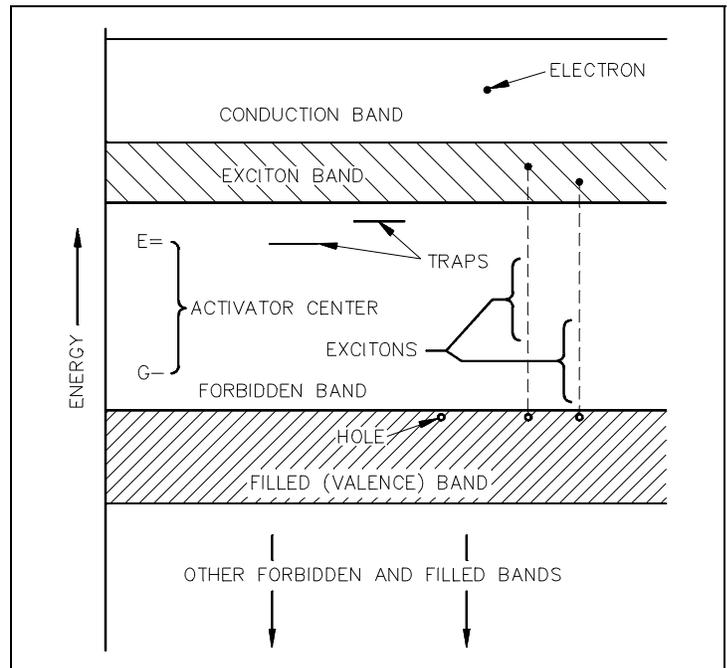


Figure 24 Electronic Energy Band of an Ionic Crystal

Scintillation counters are constructed by coupling a suitable scintillation phosphor to a light-sensitive photomultiplier tube. Figure 25 illustrates an example of a scintillation counter using a thallium-activated sodium iodide crystal.

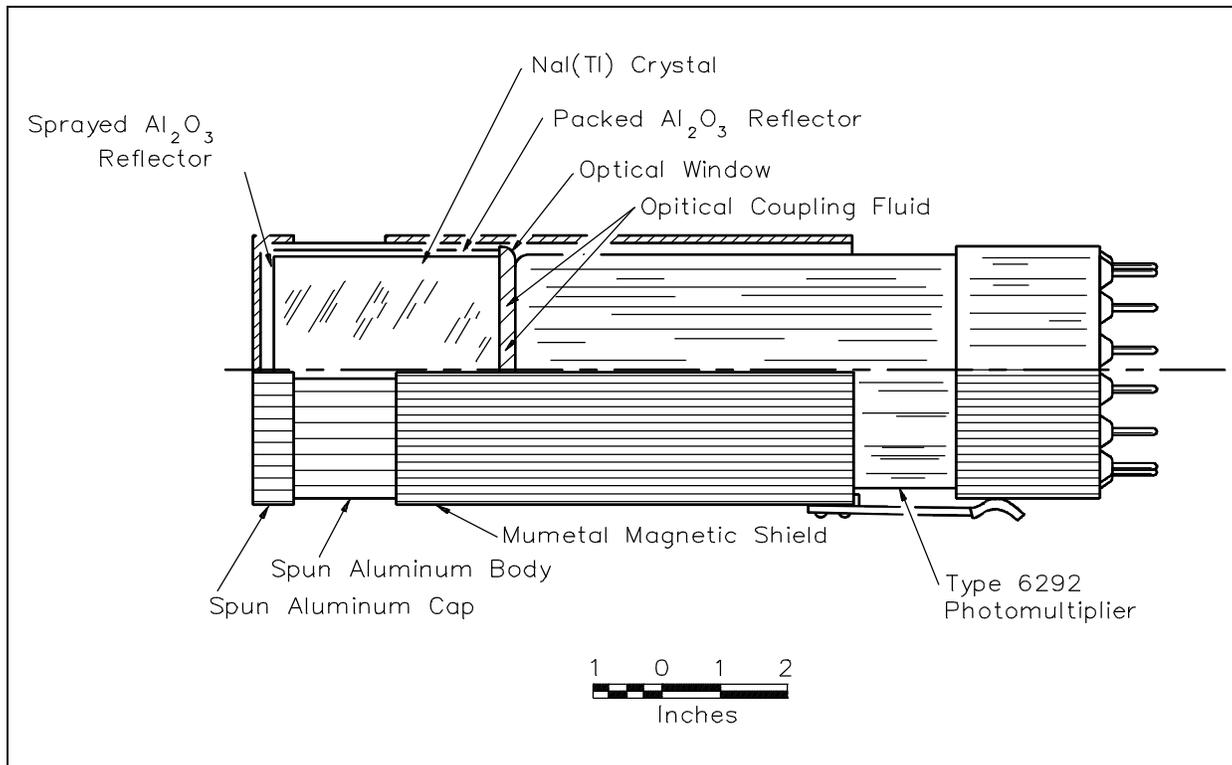


Figure 25 Scintillation Counter

There are three classes of solid state scintillation phosphors: organic crystals, inorganic crystals, and plastic phosphors.

Inorganic crystals include lithium iodide (LiI), sodium iodide (NaI), cesium iodide (CsI), and zinc sulfide (ZnS). Inorganic crystals are characterized by high density, high atomic number, and pulse decay times of approximately 1 microsecond. Thus, they exhibit high efficiency for detection of gamma rays and are capable of handling high count rates.

Organic scintillation phosphors include naphthalene, stilbene, and anthracene. The decay time of this type of phosphor is approximately 10 nanoseconds. This type of crystal is frequently used in the detection of beta particles.

Plastic phosphors are made by adding scintillation chemicals to a plastic matrix. The decay constant is the shortest of the three phosphor types, approaching 1 or 2 nanoseconds. The plastic has a high hydrogen content; therefore, it is useful for fast neutron detectors.

A schematic cross-section of one type of photomultiplier tube is shown in Figure 26. The photomultiplier is a vacuum tube with a glass envelope containing a photocathode and a series of electrodes called dynodes. Light from a scintillation phosphor liberates electrons from the photocathode by the photoelectric effect. These electrons are not of sufficient number or energy to be detected reliably by conventional electronics. However, in the photomultiplier tube, they are attracted by a voltage drop of about 50 volts to the nearest dynode.

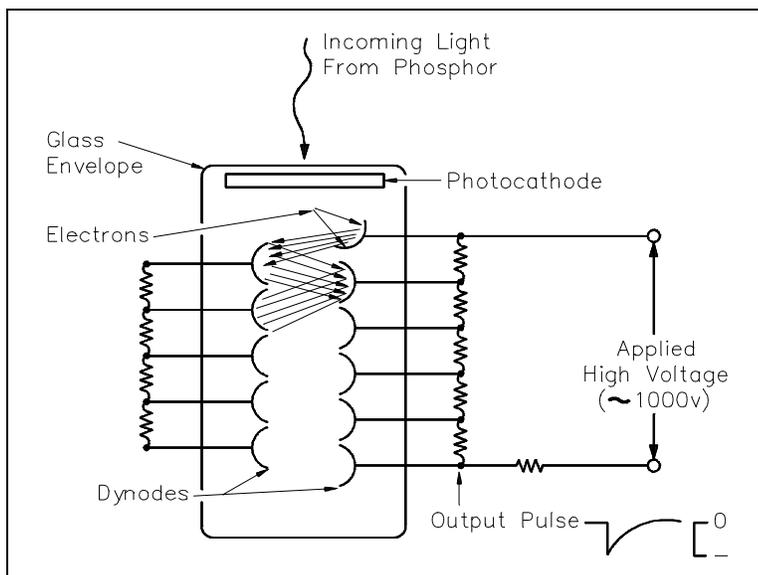


Figure 26 Photomultiplier Tube Schematic Diagram

The photoelectrons strike the first dynode with sufficient energy to liberate several new electrons for each photoelectron. The second-generation electrons are, in turn, attracted to the second dynode where a larger third-generation group of electrons is emitted. This amplification continues through 10 to 12 stages. At the last dynode, sufficient electrons are available to form a current pulse suitable for further amplification by transistor circuits. The voltage drops between dynodes are established by a single external bias, approximately 1000 volts dc, and a network of external resistors to equalize the voltage drops.

The advantages of a scintillation counter are its efficiency and the high precision and counting rates that are possible. These latter attributes are a consequence of the extremely short duration of the light flashes, from about  $10^{-9}$  to  $10^{-6}$  seconds. The intensity of the light flash and the amplitude of the output voltage pulse are proportional to the energy of the particle responsible for the flash. Consequently, scintillation counters can be used to determine the energy, as well as the number, of the exciting particles (or gamma photons). The photomultiplier tube output is very useful in radiation spectrometry (determination of incident radiation energy levels).

## **Summary**

The operation of scintillation counters is summarized below.

### **Scintillation Counter Summary**

- Radiation interactions with a crystal center cause electrons to be raised to an excited state.
- When the center de-excites, the crystal emits a photon in the visible light range.
- Three classes of phosphors are used: inorganic crystals, organic crystals, and plastic phosphors.
- The photon, emitted from the phosphor, interacts with the photocathode of a photomultiplier tube, releasing electrons.
- Using a voltage potential, the electrons are attracted and strike the nearest dynode with enough energy to release additional electrons.
- The second-generation electrons are attracted and strike a second dynode, releasing more electrons.
- This amplification continues through 10 to 12 stages.
- At the final dynode, sufficient electrons are available to produce a pulse of sufficient magnitude for further amplification.

## GAMMA SPECTROSCOPY

*Gamma spectroscopy is a radiochemistry measurement method which determines the energy and count rate of gamma rays emitted by radioactive substances.*

**EO 2.8 DESCRIBE the operation of a gamma spectrometer to include:**

- a. Type of detector used**
- b. Multichannel analyzer operation**

Gamma spectroscopy is a radiochemistry measurement method that determines the energy and count rate of gamma rays emitted by radioactive substances. Gamma spectroscopy is an extremely important measurement. A detailed analysis of the gamma ray energy spectrum is used to determine the identity and quantity of gamma emitters present in a material.

The equipment used in gamma spectroscopy includes a detector, a pulse sorter (multichannel analyzer), and associated amplifiers and data readout devices. The detector is normally a sodium iodide (NaI) scintillation counter. Figure 27 shows a block diagram of a gamma spectrometer.

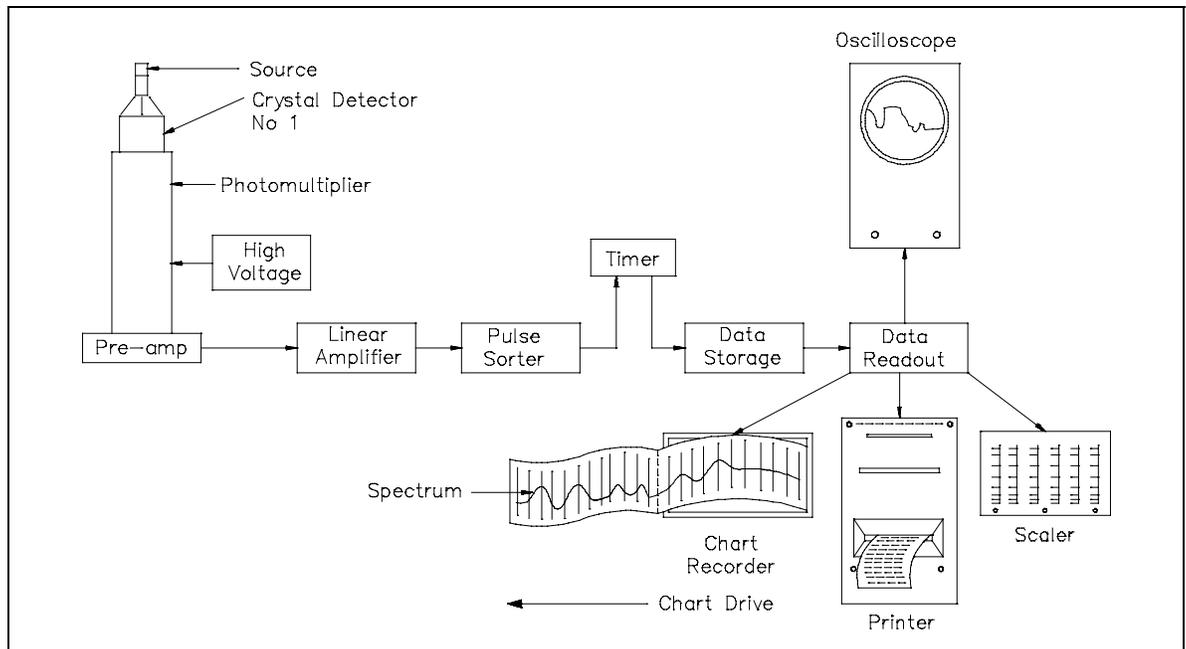


Figure 27 Gamma Spectrometer Block Diagram

The multichannel pulse height analyzer is a device that will separate pulses based on pulse height. Each energy range of pulse height is referred to as a channel. The pulse height is proportional to the energy lost by a gamma ray. Separation of the pulses, based on pulse height, shows the energy spectrum of the gamma rays that are emitted. Multichannel analyzers typically have 100 or 200 channels over an energy range of 0 to 2 MeV. The output is a plot of pulse height and gamma activity, as shown in Figure 28. By analyzing the spectrum of gamma rays emitted, the user can determine the elements which caused the gamma pulses.

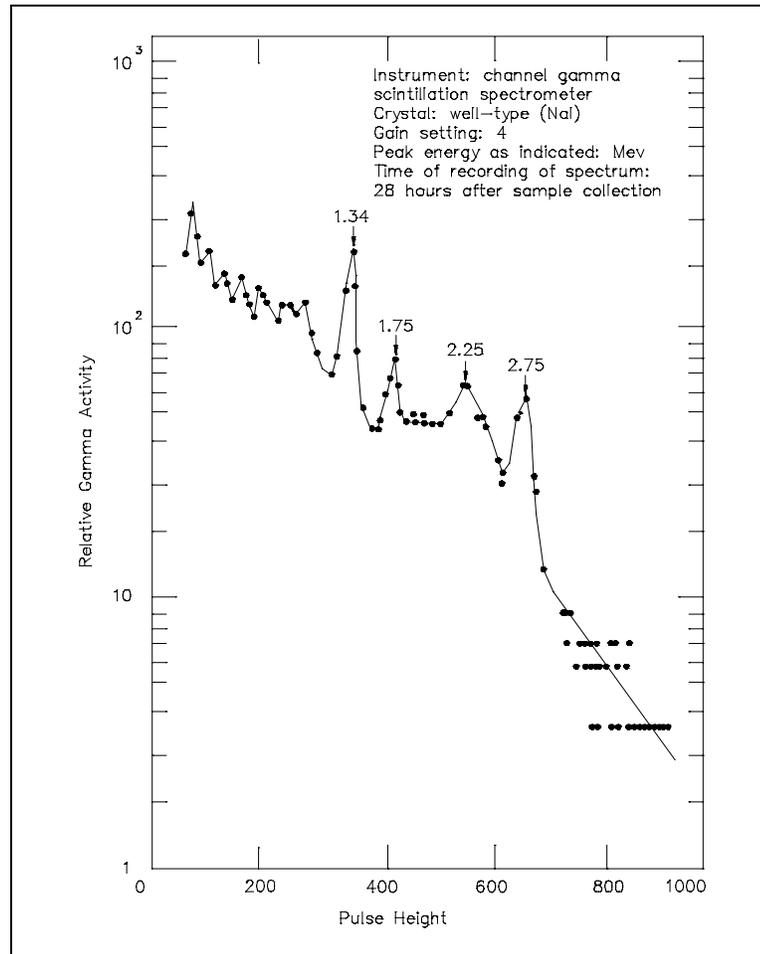


Figure 28 Multichannel Analyzer Output

## Summary

The operation of a gamma spectrometer is summarized below.

### **Gamma Spectrometer Summary**

- A gamma spectrometer uses a scintillation counter, normally NaI.
- A multichannel analyzer separates the pulses based on pulse height.
- Since each radioactive material emits gammas of certain energy levels, each pulse height corresponds to a different type of atom.

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## MISCELLANEOUS DETECTORS

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Four other types of radiation detectors are the self-powered neutron detector, wide range fission chamber, flux wire, and photographic film.

- EO 2.9**      **DESCRIBE** how the following detect neutrons:
- Self-powered neutron detector**
  - Wide range fission chamber**
  - Flux wire**

- EO 2.10**      **DESCRIBE** how a photographic film is used to measure the following:
- Total radiation dose**
  - Neutron dose**

---

### Self-Powered Neutron Detector

In very large reactor plants, the need exists to monitor neutron flux in various portions of the core on a continuous basis. This allows for quick detection of instability in any section of the core. This need brought about the development of the self-powered neutron detector that is small, inexpensive, and rugged enough to withstand the in-core environment. The self-powered neutron detector requires no voltage supply for operation. Figure 29 illustrates a simplified drawing of a self-powered neutron detector.

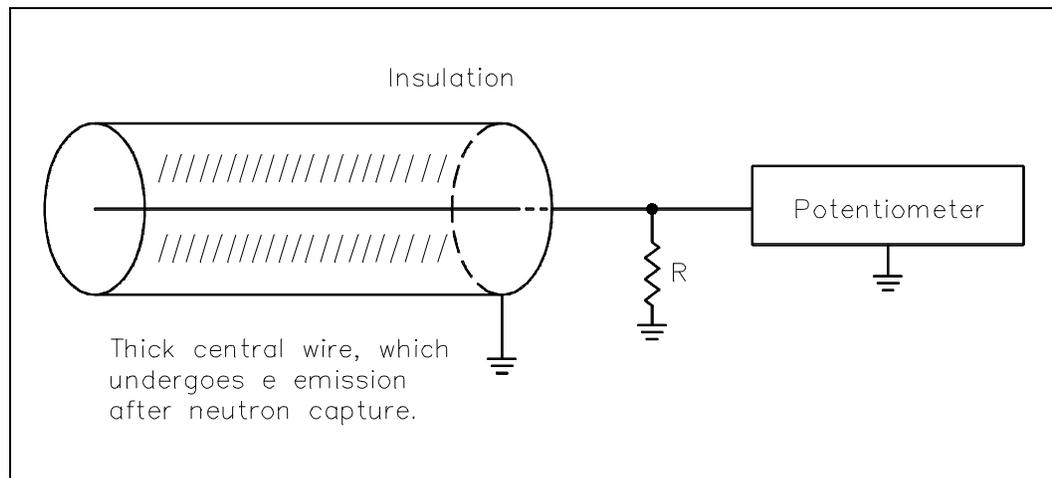


Figure 29 Self-Powered Neutron Detector

The central wire of a self-powered neutron detector is made from a material that absorbs a neutron and undergoes radioactive decay by emitting an electron (beta decay). Typical materials used for the central wire are cobalt, cadmium, rhodium, and vanadium. A good insulating material is placed between the central wire and the detector casing. Each time a neutron interacts with the central wire it transforms one of the wire's atoms into a radioactive nucleus. The nucleus eventually decays by the emission of an electron. Because of the emission of these electrons, the wire becomes more and more positively charged. The positive potential of the wire causes a current to flow in resistor, R. A millivoltmeter measures the voltage drop across the resistor. The electron current from beta decay can also be measured directly with an electrometer.

There are two distinct advantages of the self-powered neutron detector: (a) very little instrumentation is required--only a millivoltmeter or an electrometer, and (b) the emitter material has a much greater lifetime than boron or  $U^{235}$  lining (used in wide range fission chambers).

One disadvantage of the self-powered neutron detector is that the emitter material decays with a characteristic half-life. In the case of rhodium and vanadium, which are two of the most useful materials, the half-lives are 1 minute and 3.8 minutes, respectively. This means that the detector cannot respond immediately to a change in neutron flux, but takes as long as 3.8 minutes to reach 63% of steady-state value. This disadvantage is overcome by using cobalt or cadmium emitters which emit their electrons within  $10^{-14}$  seconds after neutron capture. Self-powered neutron detectors which use cobalt or cadmium are called prompt self-powered neutron detectors.

### **Wide Range Fission Chamber**

Fission chambers use neutron-induced fission to detect neutrons. The chamber is usually similar in construction to that of an ionization chamber, except that the coating material is highly enriched  $U^{235}$ . The neutrons interact with the  $U^{235}$ , causing fission. One of the two fission fragments enters the chamber, while the other fission fragment embeds itself in the chamber wall.

One advantage of using  $U^{235}$  coating rather than boron is that the fission fragment has a much higher energy level than the alpha particle from a boron reaction. Neutron-induced fission fragments produce many more ionizations in the chamber per interaction than do the neutron-induced alpha particles. This allows the fission chambers to operate in higher gamma fields than an uncompensated ion chamber with boron lining. Fission chambers are often used as current indicating devices and pulse devices simultaneously. They are especially useful as pulse chambers, due to the very large pulse size difference between neutrons and gamma rays. Because of the fission chamber's dual use, it is often used in "wide range" channels in nuclear instrumentation systems. Fission chambers are also capable of operating over the source and intermediate ranges of neutron levels.

### **Activation Foils and Flux Wires**

Whenever it is necessary to measure reactor neutron flux profiles, a section of wire or foil is inserted directly into the reactor core. The wire or foil remains in the core for the length of time required for activation to the desired level. The cross-section of the flux wire or foil must be known to obtain an accurate flux profile. After activation, the flux wire or foil is rapidly removed from the reactor core and the activity counted.

Activated foils can also discriminate energy levels by placing a cover over the foil to filter out (absorb) certain energy level neutrons. Cadmium covers are typically used for this purpose. The cadmium cover effectively filters out all of the thermal neutrons.

### **Photographic Film**

Photographic film may be utilized in x-ray work and dosimetry. The film tends to darken when exposed to radiation. This general darkening of the film is used to determine overall radiation exposure. Neutron scattering produces individual proton recoil tracks. Counting the tracks yields the film's exposure to fast neutrons. Filters are used to determine the energy and type of radiation. Some typical filters used are aluminum, copper, cadmium, or lead. These filters provide varying amounts of shielding for the attenuation of different energies. By comparing the exposure under the different filters, an approximate spectrum is determined.

## **Summary**

A description of how self-powered neutron detectors, wide range fission chambers, flux wires, and photographic film detect radiation is summarized below.

### **Miscellaneous Detector Summary**

#### Self-powered neutron detector

- The central wire, made of a neutron-absorbing material, absorbs a neutron and undergoes beta decay.
- As more beta decays occur, the remaining atoms cause the wire to become more positively charged.
- The voltage potential set up causes a current flow in a resistor, which is measured by either a millivoltmeter or electrometer.

#### Wide range fission chamber

- Neutrons interact with the  $U^{235}$  coated chamber causing fission of the  $U^{235}$ .
- A highly positive charged fission fragment interacts with the detector gas and causes ionizations.
- The electrons produced are collected as pulses on the electrode.

#### Flux wire

- The wire is inserted directly into the core and becomes activated by the neutron flux.
- When the desired activation time is reached, the wire is removed from the core and counted.

#### Photographic film

- Detects total radiation dose by darkening; film darkness determines overall exposure.
- Fast neutron exposure determined by counting individual proton recoil tracks.

## CIRCUITRY AND CIRCUIT ELEMENTS

---

*Understanding how the reactor power monitoring detection equipment works requires a working knowledge of basic terminology.*

- EO 3.1**      **DEFINE the following terms:**
- a.      **Signal-to-noise ratio**
  - b.      **Discriminator**
  - c.      **Analog**
  - d.      **Logarithm**
  - e.      **Period**
  - f.      **Decades per minute (DPM)**
  - g.      **Scalar**

- EO 3.2**      **LIST the type of detector used in each of the following nuclear instruments:**
- a.      **Source range**
  - b.      **Intermediate range**
  - c.      **Power range**
- 

### Terminology

Understanding how the reactor power monitoring detection equipment works requires a working knowledge of basic terminology.

#### Signal-to-Noise Ratio

Signal-to-noise ratio is the ratio of the electrical output signal to the electrical noise generated in the cable run or in the instrumentation.

#### Discriminator

Discrimination in radiation detection circuits refers to the process of distinguishing between different types of radiation on the basis of pulse height. A discriminator circuit selects the minimum or maximum pulse height that is to be counted.

## **Analog**

Analog is defined as a mechanism in which data is represented by continuously variable physical quantities. As it applies to the intermediate range, the output of the intermediate range is an analog current. Due to the wide range of the flux measured, use of logarithmic circuitry is required for indication on a single scale instrument. Analog is used in contrast to digital to refer to circuits in which the magnitude of the signal carries the information. Figure 30(A) illustrates an example of an analog display, and 30(B) illustrates a digital display.

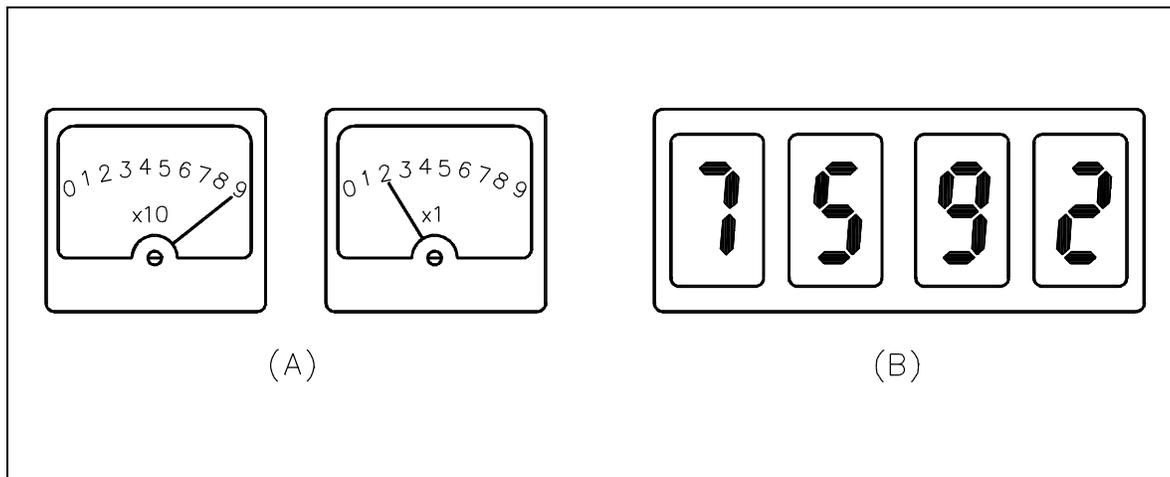


Figure 30 Analog and Digital Displays

## **Logarithm**

Logarithm is defined as the exponent that indicates the power to which a number is raised to produce a given number (i.e., the logarithm of 100 to the base 10 is 2).

When discussing nuclear instrumentation, this term refers to the electronic circuitry of the source and intermediate ranges. These ranges utilize logarithms due to the wide range of measured flux and the necessity to measure that flux on a single meter scale.

## **Reactor Period**

Reactor period is defined as that amount of time, normally in seconds, required for neutron flux (power) to change by a factor of  $e$ , or 2.718.

### **Decades Per Minute (DPM)**

Rate circuits are important in the source and intermediate ranges. Rate information is displayed on a meter in decades per minute. These meters indicate how fast reactor power is changing in decades (power of 10) in each minute.

### **Scalar**

This term refers to a measurement or quantity that is capable of being represented on a scale (i.e., neutron flux on source range, intermediate range, and power range meters).

### **Components**

Three ranges are used to monitor the power level of a reactor throughout the full range of reactor operation: source range, intermediate range, and power range. The source range normally uses a proportional counter, while the intermediate and power ranges use ionization chambers. A compensated ion chamber is used for the intermediate range. The power range uses an uncompensated ion chamber. Each of the three different ranges makes use of some or all of the following types of components.

### **Preamplifiers and Amplifiers**

Radiation detector output signals are usually weak and require amplification before they can be used. In radiation detection circuits, the nature of the input pulse and discriminator determines the characteristics that the preamplifier and amplifier must have. Two stages of amplification are used in most detection circuits to increase the signal-to-noise ratio.

Figure 31 shows how a two-stage amplifier increases the signal-to-noise ratio.

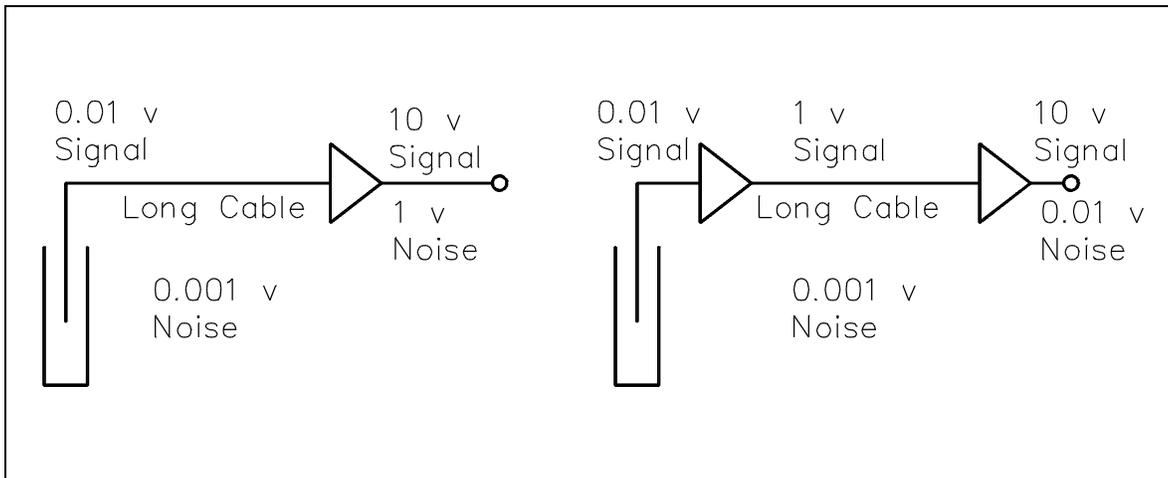


Figure 31 Single and Two-Stage Amplifier Circuits

The radiation detector is located some distance from the readout. A shielded coaxial cable transmits the detector output to the amplifier. The output signal of the detector may be as low as 0.01 volts. A total gain of 1000 is needed to increase this signal to 10 volts, which is a usable output pulse voltage. There is always a pickup of noise in the long cable run; this noise can amount to 0.001 volts.

If all amplification were done at the remote amplifier, the 0.01-volt pulse signal would be 10 volts, and the 0.001 noise signal would be 1 volt. This is a signal-to-noise ratio of 10 and could be significantly reduced by dividing the total gain between two stages of amplification. A preamplifier located near the detector and a remote amplifier could be used. The preamplifier virtually eliminates cable noise because of the short cable length. If, for a total gain of 1000, the preamplifier has a gain of 100 and the amplifier has a gain of 10, the output signal from the preamplifier is 1 volt. The signal transmitted via the long cable run still picks up the 0.001-volt noise. The amplifier amplifies the 1.0-volt pulse signal and the 0.001-volt noise signal by a factor of 10. The result is a 10-volt pulse signal and a 0.01-volt noise signal. This gives a signal-to-noise ratio of 1000.

## Discriminator Circuit

A discriminator circuit selects the minimum pulse height. When the input pulse exceeds the discriminator preset level, the discriminator generates an output pulse. The discriminator input is normally an amplified and shaped detector signal. This signal is an analog signal because the amplitude is proportional to the energy of the incident particle.

The biased diode circuit is the simplest form of discriminator. Figure 32 shows a biased diode discriminator circuit with its associated input and output signals.

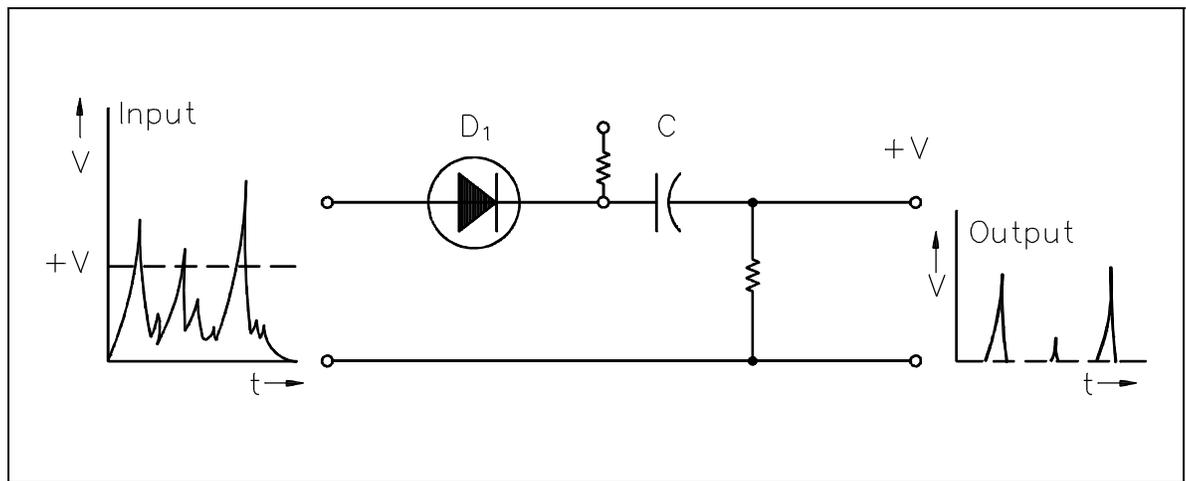


Figure 32 Biased Diode Discriminator

Diode  $D_1$  is shown with its cathode connected to a positive voltage source  $+V$ . A diode cannot conduct unless the voltage across the anode is positive with respect to the cathode. As long as the voltage at the anode is less than that of the cathode, diode  $D_1$  does not conduct, and there is no output. At some point, anode voltage exceeds the bias value  $+V$ , and the diode conducts. The input signal is allowed to pass to the output.

Figure 32 illustrates input and output signals and how the discriminator acts to eliminate all pulses that are below the preset level. The output pulses of this circuit have the same relative amplitudes as the input pulses.

## Logarithmic Meters

Radiation detection circuit currents or pulse rates vary over a wide range of values. The current output of an ionization chamber may vary by 8 orders of magnitude. For example, the range may be from  $10^{-13}$  amps to  $10^{-5}$  amps. The most accurate method to display this range would be to utilize a linear current meter with several scales, and the capability to switch those scales. This is not practical. A single scale which covers the entire range of values is used. This scale is referred to as logarithmic.

The logarithmic output meter must be provided with a signal which is proportional to the logarithm of the input signal. This is easily done by using a diode when the input signal is from an ionization chamber. The voltage across the diode equals the logarithm of the current through the diode. Using this principle, the simplified circuit, shown in Figure 33, is used to convert ionization chamber current to a voltage proportional to the logarithm of this current.

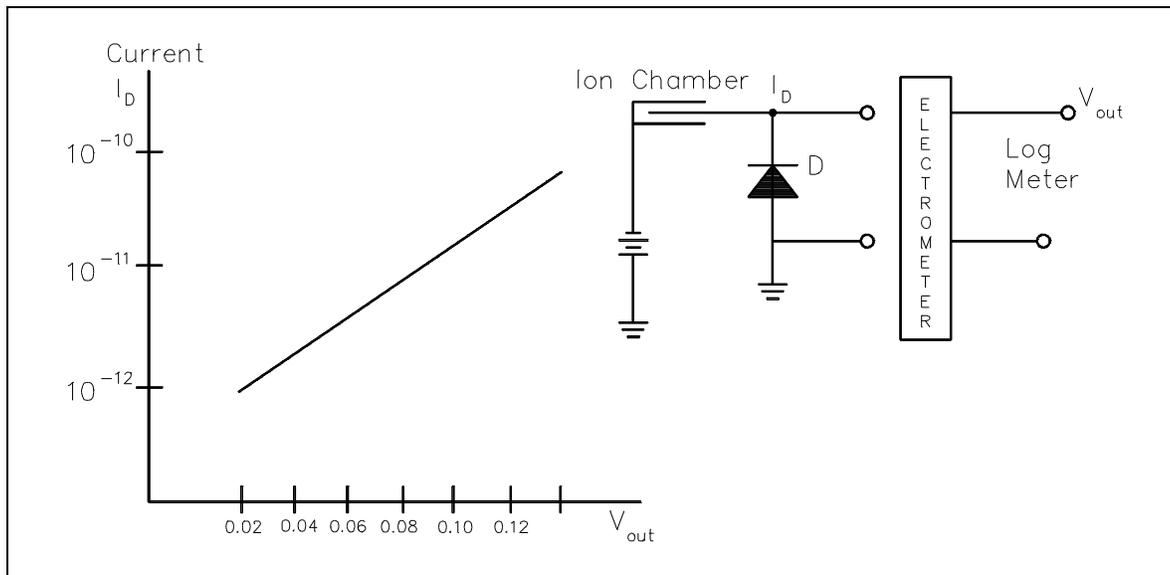


Figure 33 Log Count Rate Meter

## Period Meters and Startup Rate

In many applications it is essential to know the rate of change of power. This rate normally increases or decreases exponentially with time. The time constant for this change is referred to as the period. A period of five seconds means that the value changes by a factor of  $e$  (2.718) in five seconds. Figure 34 shows a basic period meter circuit.

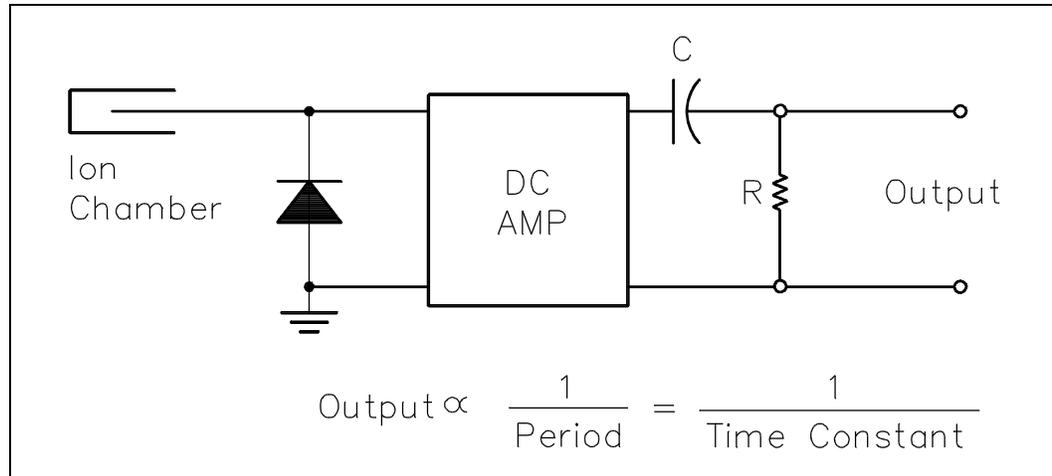


Figure 34 Period Meter Circuit

Placing the signal through an RC circuit causes a voltage that is proportional to the reciprocal of the period. If the current output from the ionization chamber is constant, no current flows through resistor R, and the output voltage is zero. This corresponds to an infinite period. As the ion chamber output current changes, there is a voltage transient across capacitor C, and current flows through resistor R. The more rapid the transient, the greater the voltage drop across resistor R, and the shorter the period.

Rate information is displayed on a meter in decades per minute, and since it is used by the operator to monitor the rate of change of power during startup, it is termed startup rate. Startup rate (SUR) equates to reactor period using Equation 6-10.

$$\text{SUR} = \frac{26.06}{\tau} \quad (6-10)$$

where

SUR = startup rate in decades per minute

26.06 = constant

$\tau$  = reactor period in seconds

The reactor operator adjusts control rods so that an upper limit, such as 1 DPM, is not exceeded. This allows an orderly increase in reactor power.

## **Summary**

The source range uses a proportional counter. The intermediate range uses a compensated ion chamber. The power range uses an uncompensated ion chamber. Terms used to describe the electrical circuits are summarized below.

### **Circuit Terminology Summary**

- Signal-to-noise ratio is the ratio of the electrical output signal to the electrical noise generated.
- A discriminator selects the minimum pulse height to be counted.
- Analog is a mechanism in which data is represented by continuously variable physical quantities.
- Logarithm is the exponent that indicates the power to which a number is raised to produce a given number.
- Reactor period is that amount of time required for neutron flux to change by a factor of  $e$ .
- Decades per minute is the rate at which neutron flux is changing by a power of 10 in each minute.
- Scalar is a measurement or quantity which is capable of being represented on a scale.
- Startup rate is the rate at which neutron flux is changing measured in decades per minute.

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## SOURCE RANGE NUCLEAR INSTRUMENTATION

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*Three ranges are used to monitor the power level of a reactor throughout the full range of reactor operation. The source range makes use of a proportional counter.*

- EO 3.3**      **Given a block diagram of a typical source range instrument, STATE the purpose of major components.**
- a.      Linear amplifier**
  - b.      Discriminator**
  - c.      Pulse integrator**
  - d.      Log count rate amplifier**
  - e.      Differentiator**
- 

Source range instrumentation normally consists of two redundant count rate channels, each composed of a high-sensitivity proportional counter and associated signal measuring equipment. These channels are typically used over a counting range of 0.1 to  $10^6$  counts per second, but vary based on reactor design. Their outputs are displayed on meters in terms of the logarithm of the count rate.

Source range instrumentation also measures the rate of change of the count rate. The rate of change is displayed on meters in terms of the startup rate from -1 to +10 decades per minute. Protective functions are not normally associated with source range instrumentation because of inherent limitations in this range. However, interlocks may be incorporated.

Many reactor plants have found it necessary to place source range proportional counters in lead shielding to reduce gamma flux at the detectors. This serves two functions: (a) it increases the low end sensitivity of the detector, and (b) it adds to detector life. Another means by which detector life is extended is to disable the high voltage power supply to the detector and short the signal lead when neutron flux has passed into the intermediate range. There are some reactor plants that have made provisions for moving the source range detectors from their operating positions to a position of reduced neutron flux level, once the flux level increases above the source range.

Figure 35 shows a typical source range channel in functional form.

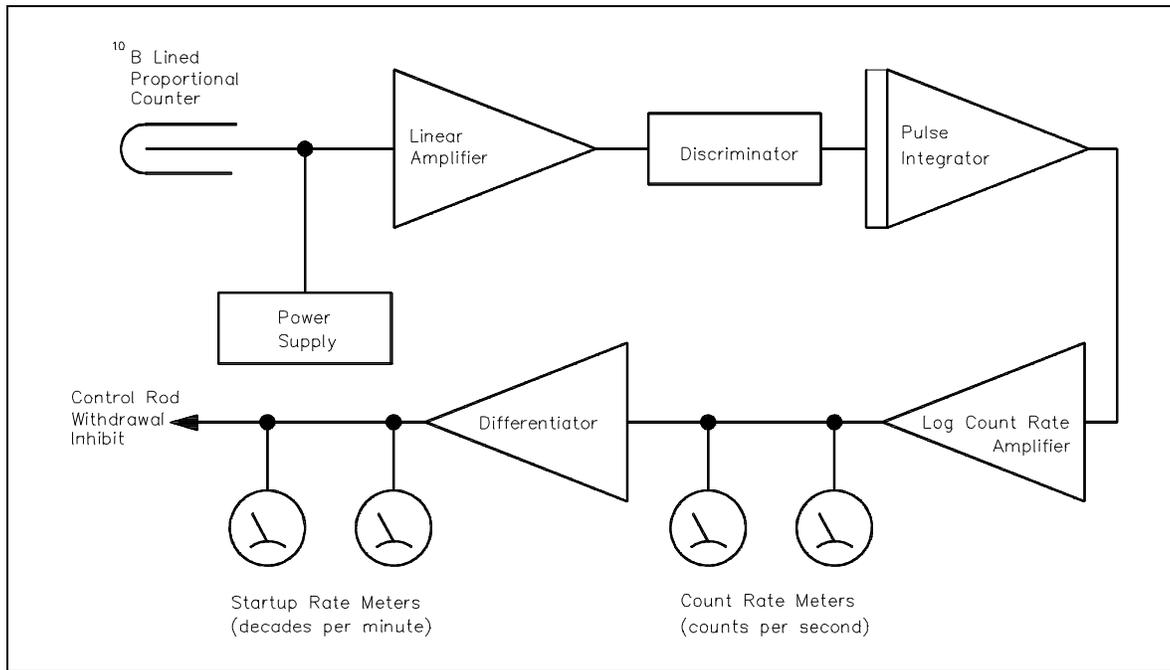


Figure 35 Source Range Channel

$\text{B}^{10}$  lined or  $\text{BF}_3$  gas-filled proportional counters are normally used as source range detectors. Proportional counter output is in the form of one pulse for every ionizing event; therefore, there is a series of random pulses varying in magnitude representing neutron and gamma ionizing events.

The pulse height may only be a few millivolts, which is too low to be directly used without amplification. The linear amplifier amplifies the input signal by a factor of several thousand to raise the pulse height to several volts.

The discriminator excludes passage of pulses that are less than a predetermined level. The function of the discriminator is to exclude noise and gamma pulses that are lower in magnitude than neutron pulses.

The pulses are then sent to the pulse integrator where they are integrated to give a signal that is proportional to the logarithm of the count rate.

The log count rate amplifier then amplifies the signal, which varies directly as the logarithm of the pulse rate, in the detector. The logarithmic count rate is then displayed on a meter with a logarithmic scale in counts per second.

The logarithmic count rate signal is differentiated to measure the rate of change in neutron flux. The differentiator output is proportional to reactor period. The value of reactor period is inversely proportional to the actual rate of change of reactor power and relates to power changes by factors of  $e$  (2.718). The power rate change based on factors of 10, in decades per minute, is more meaningful to the reactor operator. Therefore, the output of the differentiator is converted from reactor period to decades per minute through the meter scale used.

### **Summary**

The purposes of source range components are summarized below.

#### **Source Range Instrumentation Summary**

- The **linear amplifier** amplifies the input signal by a factor of several thousand to raise the pulse height to several volts.
- The **discriminator** excludes passage of pulses that are less than a predetermined level.
- The **pulse integrator** provides an output signal proportional to the logarithm of the count rate.
- The **log count rate amplifier** amplifies the signal for display on a meter.
- The **differentiator** provides an output signal proportional to the rate of power change.

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## INTERMEDIATE RANGE NUCLEAR INSTRUMENTATION

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*Three ranges are used to monitor the power level of a reactor throughout the full range of reactor operation. The intermediate range makes use of a compensated ion chamber.*

**EO 3.4**      **Given a block diagram of a typical intermediate range instrument, STATE the purpose of major components.**

- a.      Log n amplifier**
  - b.      Differentiator**
  - c.      Reactor protection interface**
- 

Intermediate-range nuclear instrumentation consists of a minimum of two redundant channels. Each of these channels is made up of a boron-lined or boron gas-filled compensated ion chamber and associated signal measuring equipment of which the output is a steady current produced by the neutron flux.

The compensated ion chamber is utilized in the intermediate range because the current output is proportional to the relatively stable neutron flux, and it compensates for signals from gamma flux. This range of indication also provides a measure of the rate of change of neutron level. This rate of change is displayed on meters in terms of startup rate in decades per minute (-1 to +10 decades per minute). High startup rate on either channel may initiate a protective action. This protective action may be in the form of a control rod withdrawal inhibit and alarm, or a high startup rate reactor trip.

Figure 36 shows a typical intermediate-range channel.

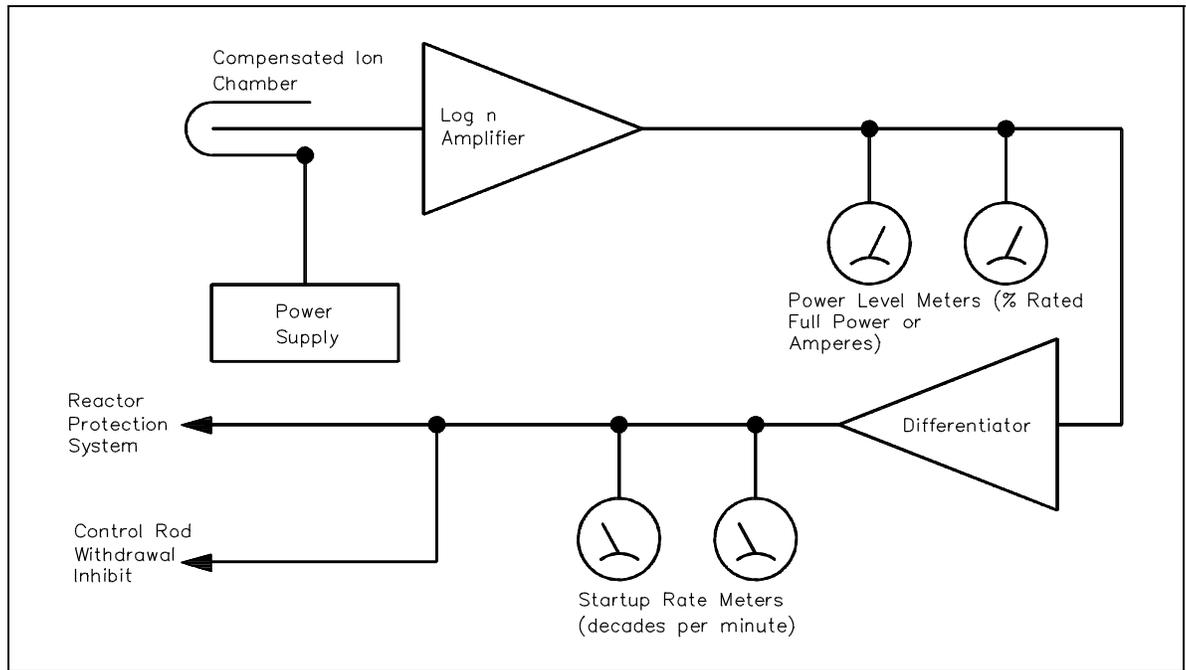


Figure 36 Intermediate Range Channel

Typically, the compensated ion chamber output is an analog current ranging from  $10^{-11}$  to  $10^{-3}$  amperes, but varies with reactor design. The log n amplifier is a logarithmic current amplifier that converts the detector output to a signal proportional to the logarithm of the detector current. This logarithmic output is proportional to the logarithm of the neutron level.

The determination of rate change of the logarithm of the neutron level, as in the source range, is accomplished by the differentiator. The differentiator measures reactor period or startup rate. Startup rate in the intermediate range is more stable because the neutron level signal is subject to less sudden large variations. For this reason, intermediate-range startup rate is often used as an input to the reactor protection system.

The reactor protective interface provides signals for protective actions. Examples of protective actions include control rod withdrawal interlocks and startup rate reactor trips.

## **Summary**

The purposes of intermediate range components are summarized below.

### **Intermediate Range Instrumentation Summary**

- The log n amplifier converts the detector output signal to a signal proportional to the logarithm of the detector current.
- The differentiator provides an output proportional to the rate of change of power.
- The reactor protection interface provides signals for protective actions.

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## POWER RANGE NUCLEAR INSTRUMENTATION

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*Three ranges are used to monitor the power level of a reactor throughout the full range of reactor operation. The power range makes use of an uncompensated ion chamber.*

**EO 3.5      STATE the reason gamma compensation is NOT required in the power range.**

**EO 3.6      Given a block diagram of a typical power range instrument, STATE the purpose of major components.**

- a.      Linear amplifier**
- b.      Reactor protection interface**

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Power range nuclear instrumentation normally consists of four identical linear power level channels which originate in eight uncompensated ion chambers. The output is a steady current produced by the neutron flux. Uncompensated ion chambers are utilized in the power range because gamma compensation is unnecessary; the neutron-to-gamma flux ratio is high. Having a high neutron-to-gamma flux ratio means that the number of gammas is insignificant compared to the number of neutrons.

The output of each power range channel is directly proportional to reactor power and typically covers a range from 0% to 125% of full power, but varies with each reactor. The output of each channel is displayed on a meter in terms of power level in percent of full rated power. The gain of each instrument is adjustable which provides a means for calibrating the output. This adjustment is normally determined by using a plant heat balance. Protective actions may be initiated by high power level on any two channels; this is termed coincidence operation.

Figure 37 shows a typical power range channel.

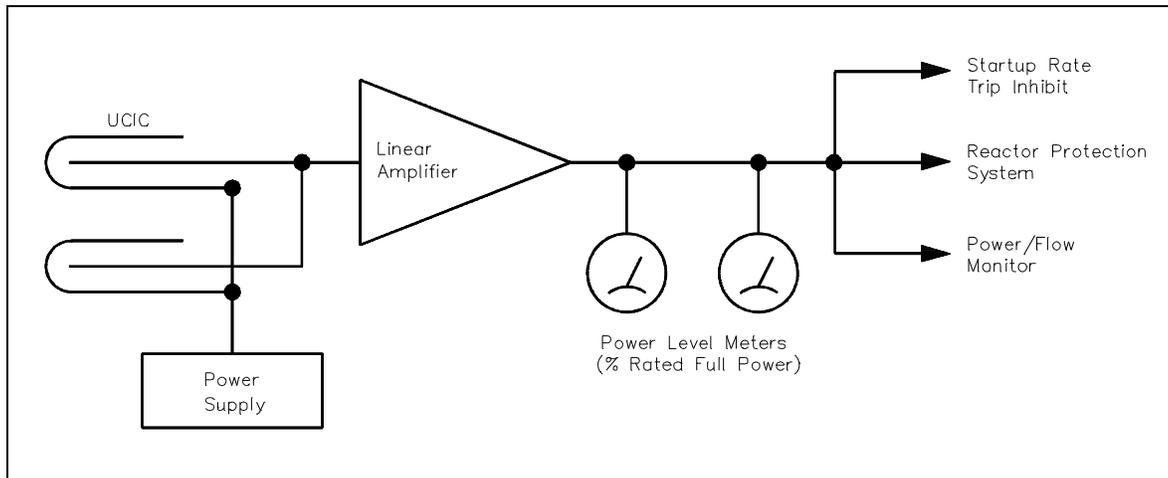


Figure 37 Power Range Channel

Two detectors in each channel are functionally connected in parallel so that the measured signal is the sum of the two detectors. This output drives a linear amplifier which amplifies the signal to a useful level.

The reactor protective interface provides signals for protective actions. Examples of protective action signals provided by the power range include:

- A signal to the reactor protection system at a selected value (normally 10% reactor power) to disable the high startup rate reactor trip
- A signal to protective systems when reactor power level exceeds predetermined values
- A signal for use in the reactor control system
- A signal to the power-to-flow circuit

## **Summary**

Gamma compensation is NOT required in the power range since neutrons outnumber gammas by such a large number that gammas are insignificant. The purposes of power range components are summarized below.

### **Power Range Instrumentation Summary**

- The **linear amplifier** amplifies the signal to a useful level.
- The **reactor protective** interface provides signals for protective actions.