Radiation Protection

Radiation Detection and Instrumentation

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INTRODUCTION

We have learned that ionizing radiation has the ability to transfer energy to the material through which it passes. If the radiation were to pass through human tissue, that tissue would absorb some energy. The absorption of energy is not enough to stimulate nerve endings, so we could be exposed to large amounts of radiation and not feel our bodies absorbing the energy. In fact, we could receive a lethal dose of radiation and not know it until the effects became apparent hours or days later. If we cannot detect radiation as we can detect smell, heat, or light, how do we know if we are exposed to radiation? Obviously, we need an instrument to do the detecting. This lesson will discuss radiation detection instrumentation construction and operation.

OBJECTIVES

TERMINAL OBJECTIVE

The Contractor Health Physics Technician will be able to select the appropriate radiation survey instrument for a given job and justify why the selected instrument was chosen. The Contractor Health Physics Technician will describe the basic concepts of dosimetry and the principles of operation and characteristics of the various types of dosimetry.

ENABLING OBJECTIVES

Upon completion of this lesson, the Contractor Health Physics Technician will be able to:

1. Explain how ionization can be used to detect radiation.
2. Explain the basic principal of operation for a typical gas-filled detector circuit.
3. Describe the basic operating characteristics of the ionization chamber.
4. Describe the basic operation characteristics of a proportional counter.
5. Explain how a proportional counter can discriminate between different types of radiation.
6. Explain how a proportional counter can be made to measure neutron dose rates.
7. List the radiation measurement instruments in the plant that use proportional counters.
8. Describe the basic operating characteristics of a Geiger-Mueller detector.
9. Explain why scintillation detectors are more sensitive than gas-filled detectors.
10. Explain the basic operation of a scintillation detector.
11. Explain the basic operation of a semi-conductor detector.
12. Define MDC, MDA, and LLD using the terminology of radiological counting.
13. Describe errors and problems inherent in relating dosimeter readings to actual dose.
14. Describe the principles of operation and characteristics of:

      a.   Thermoluminescent dosimeters (TLD's)

      b.   Pocket Ion Chambers

      c.   Extremity Monitors (i.e., finger rings)

15. Describe the methods used to assess beta dose.
16. Describe the advantages and disadvantages of a TLD.

1.0   BASIC DETECTORS

It would be difficult to design an instrument that would directly measure gamma photons or any other type of radiation for that matter. As we have learned, a gamma photon is a packet of energy. How could we measure it? We do not measure the radiation directly but measure it's effects on the material through which it passes. We do this by measuring the ionization that occurs in a material through which radiation passes.

Radiation detection instruments consist of three basic parts:

- A detector chamber
- A power supply/amplification system
- A measuring device/meter

As radiation passes through the detector chamber it will interact with either the chamber walls or the material with the chamber. The output of the chamber is amplified and processed by the measuring device giving us a useful reading of the amount of radiation present. The reading can tell us the relative intensity of the radiation present.

Since this is not an electronics course, we will not discuss how the actual amplification and measurement is accomplished. We will explore the principles of radiation detection and the characteristics of different types of detectors.

As you will remember, ionization is the production of ion pairs a positively charged ion and a negatively charged ion. Detection systems that measure ionization have the same basic components as other radiation detection systems. Figure RP-3-1 is a schematic of this type of system.
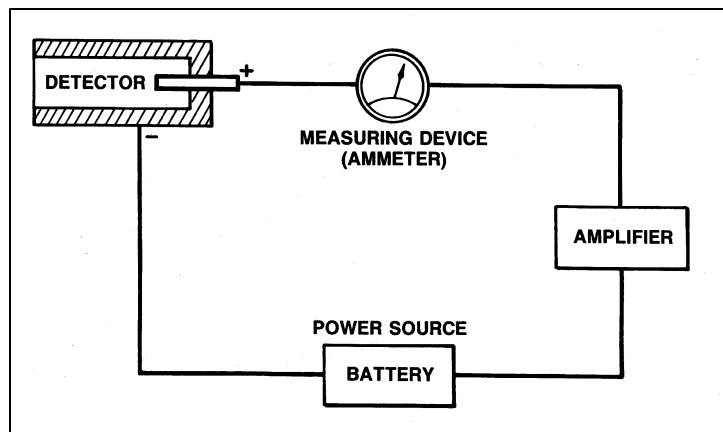
**P-3-1 Basic System for Measuring Ionization**

The battery (power supply) in the circuit effectively creates positive and negative poles (or electrodes) at the detector. The center wire or rod is the positive electrode and the walls of the chamber are the negative electrode. As the figure shows, the positive

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electrode is isolated from the negative electrode. If ionizing radiation (such as a beta chamber, it will interact with the material within the chamber (usually a gas) and ion pairs will be formed. Because of the voltage differential across the electrodes, the positive ions will flow to the negative walls of the chamber, and the negative ions will flow to the positive electrode in the chamber. This ion collection results in a current flow through the circuit. As current flows through the circuit, the measuring device (meter) will deflect in proportion to the amount of ionization taking place in the chamber. This results in a useful indication of the amount of radiation that is present. When the first ions reach the electrodes, there will be a small current flow. As more and more ions reach the electrodes, the magnitude of the current flow increases until it reaches a peak. Then the number of ions reaching the electrodes begins to decrease, and the current flow begins to decrease. This goes on until all the ions have reached the electrodes.

If the amount of current measured for a single beta particle is plotted against time, a curve like the one in Figure RP-3-2 will be obtained.

This curve is called a pulse. It corresponds to one particle (or wave) of radiation passing through the detector. The size of the pulse varies, depending on the number of ion pairs produced and collected in the detector. The pulse is large if more ion pairs are collected and smaller if fewer ion pairs are collected.
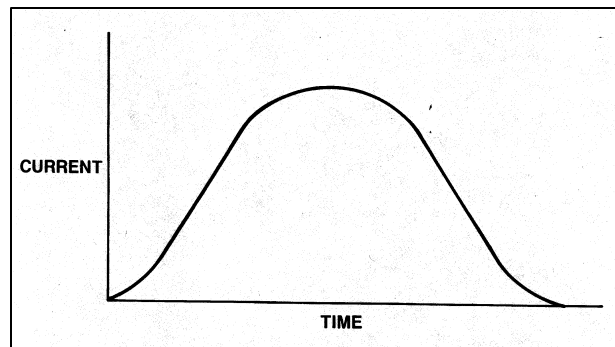
RP-3-2 Current Resulting from a Single Beta

Many factors affect the number of ion pairs that are produced and conversely the size of the pulse.

The first of these factors is the type of radiation passing through the chamber. If the radiation has a higher specific ionization, it will produce more ion pairs and a larger pulse will result. Alpha radiation has a specific ionization potential that is approximately 20 times that of gamma radiation so if the alpha particle were to interact within the chamber its resulting pulse would be much larger than the gamma interaction.

The second factor is the density of the gas in the detector. If the gas is more dense because it is under a greater pressure, there will be more ionization interactions since there are more atoms available for radiation interaction. A larger pulse will result.

The third factor is the incident energy of the radiation. A gamma photon of low energy will interact only a few times before dissipating all of its energy resulting in few ion pairs produced and a small pulse. If the incident gamma photon has a higher energy it may interact many times before dissipating its energy resulting in many more ion pairs produced and a correspondingly larger pulse.

The fourth factor is the type of gas the chamber is filled with, if the gas is easily ionized, more ion pairs will result along with a higher pulse. Generally ion chambers are filled with a counting gas such as argon.

The fifth factor is the physical size of the detector. If the detector is so small that the gamma photon passes through it without interacting, no pulse would result. Conversely, if we make the chamber large enough to allow the gamma photon to completely dissipate its energy within the confines of the tube, many ion pairs and a large pulse will result.

The sixth factor concerns the voltage applied across the electrodes of the chamber. If a very low voltage is applied it is possible that the electron pairs produced will recombine before reaching the electrodes and no pulse would result. If the voltage is very high, gas amplification can occur. Gas amplification is the production of secondary ionization by the initial ions produced by the radiation. The voltage is high enough that the electrons are accelerated as they approach the electrodes. If the electrons gain enough energy they may start to produce ionization themselves. This could result in an avalanche effect.

These six factors affect the number of ion pairs produced and the size of the pulse, which is extremely important. If the pulse produced in the detector is too small, the measuring device may not be able to sense it. The size of the pulse can also be used to determine the type of radiation entering the detector. This is referred to as pulse height analysis. We can tell whether the radiation is alpha or beta, and by counting the number of pulses, we can determine the amount of radiation that has entered the detector.

Many different types of gas-filled detectors use ionization reactions to measure radiation intensity. There are three general classifications of detectors:

- Ionization chambers
- Proportional counters
- Geiger-Mueller (GM) tubes

The thing that distinguishes one detector from another is the size of the pulse compared to the applied voltage across the electrodes.

2.0 SIX REGION CURVE

If we were to construct a graph of the relationship between ion pairs collected and applied voltage, a graph as depicted in Figure RP-3-3 would result. The figure shows pulse size (ion pairs collected) on a logarithmic axis to applied voltage on a linear axis. The curve shows what happens to pulse size as the applied voltage is increased. All other detector variables (detector size, radiation type, radiation energy, etc.) are assumed to remain constant while the pulse sizes are being measured.
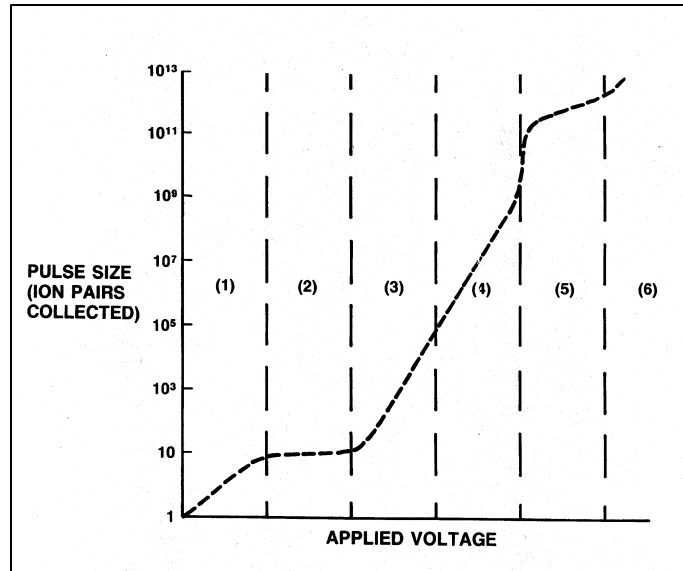
RP-3-3 Six Region Curve

Only the applied voltage is changed. You should remember that this entire curve does not apply to only one detector. Detectors are generally designed to operate in only one region of this curve, not all six regions.

The curve is divided into six distinct regions called the six region curve. Each region has a name and its own distinctive characteristics. Briefly, the six regions are:

- Recombination region applies to very low voltage; as voltage increase, the pulse size increases.
- Ionization chamber region pulse size does not change as the voltage increases.
- Proportional region pulse size increases as voltage increases.
- Limited proportional region pulse size again increases as voltage increases.
- Geiger-Mueller (GM) region pulse size increases slightly as voltage increases, but not nearly as fast as in the limited proportional region.
- Continuous discharge region pulse size is extremely large.

The six region curve is used to logically explain the characteristics and limitations of the three types of gas-filled detectors. Each type of detector will operate in the voltage range of one of the six regions of the curve. This means that the ionization chamber operates in

the ionization chamber region, the proportional counter operates in the proportional region, and the Geiger-Mueller tube operates in the Geiger-Mueller region.

2.1   RECOMBINATION REGION

The recombination region is the region of lowest applied voltage. Detectors are not operated in this region because many of the ions produced in the detectors never reach the electrodes. When ion pairs are produced in the detector, the ions move toward the appropriate electrodes, but, since the voltage is low, the ions do not mover very fast. Because of the slow movement, some of the positive ions have a chance to form neutral atoms. This results in fewer ions being collected than were produced.

In the recombination region, the actual percentage of ions that recombine before reaching the electrodes varies, even when there is a constant voltage. For this reason, detection instruments are not operated in the recombination region.

2.2   IONIZATION CHAMBER REGION

In the ionization chamber region, the applied voltage is greater than it is in the recombination region.

This portion of the six region curve is flat because there is no change in the number of ion pairs collected as the voltage increases. Every ion pair produced by radiation in the detector is collected on the electrodes. The voltage is high enough so that there is no recombination, but it is not high enough to cause gas amplification (ions moving toward the electrodes so fast that they cause additional ionization).

It is important to remember that in the ionization chamber region, the number of ion pairs collected by the electrodes is equal to the number of ion pairs produced by the radiation in the detector. The number of ion pairs collected does not vary with the voltage. That is one reason why some detection instruments are used in the ionization chamber region. Even if the voltage varies a little, the same reading is achieved.

2.3   PROPORTIONAL AND LIMITED PROPORTIONAL REGIONS

In the proportional region and the limited proportional region, the number of ions pairs collected is greater than the number of ion pairs produced in the detector by the radiation. In these two regions, there is gas amplification. A gas amplification factor is used to determine the number of ions actually produced by the radiation. The gas amplification

factor is equal to the number of ion pairs collected divided by the number of ion pairs produced by the radiation.

The gas amplification factor varies from detector to detector, and it also varies with the applied voltage across the electrodes. For example, the gas amplification factor at a certain voltage might be 5. As the voltage increases, there is more gas amplification, and the gas amplification factor might go to 10 or 100.

The group of radiation detection instruments called proportional counters is operated in the proportional region. Operation of these instruments is possible because the gas amplification factor at a specific voltage in the proportional region is the same for any type of radiation or energy of radiation. Thus, for a given voltage setting, the number of ion pairs produced by the radiation is always multiplied by the same factor. For example, if the gas amplification factor is 5, and the radiation produces 100 ion pairs, 500 ion pairs will be collected. If the radiation produces 10,000 ion pairs, 50,000 ion pairs will be collected. This is not the case in the limited proportional region, so detectors are not operated in that region. The gas amplification factor is not constant for a given voltage setting in the limited proportional region.

As long as the voltage remains constant, the number of ion pairs collected in the proportional region is proportional to the number of ion pairs originally produced in the detector by radiation. This means that operation of instruments in the proportional region requires a very stable voltage supply. Many radiation detection instruments are operated in this region because the effect of gas amplification makes the instrument sensitive to low levels of radiation.

2.4   GEIGER-MUELLER REGION

In the Geiger-Mueller (GM) region, gas amplification is increased to the point where any single ionizing event will produce so many secondary ions that a very large pulse is produced. A single beta produces a few ion pairs; these ion pairs produce more ion pairs, until literally millions of ion pairs are produced. This effect is called avalanching and is the result of the high voltage potential across the positive and negative electrodes.

When ionization occurs, the negatively charged ions (free electrons), which are much smaller than the positively charged ions, move quickly to the positive electrode. The positively charged ions, which are larger, move much more slowly. In fact, they tend to form a cloud of ions that moves gradually to the negative chamber wall. The cloud of positively charged ions effectively forms a second "positive electrode", which actually divides the large voltage potential into two smaller voltage potentials - one between the highly positive central electrode and the positively charged cloud and another between

the positively charged cloud and the negatively charged walls. Because these two smaller voltage differentials take the place of the one large voltage differential in effect two small sub-detectors are produced. The voltage potential in either of these sub-detectors is well below the applied voltage of the Geiger-Mueller region, so the avalanching stops.

When avalanching occurs, it is so great that the pulse size does not depend on the number of ion pairs produced by the radiation entering the detector. The pulse size is the same, no matter what type or energy radiation caused the ionization. For example, a small beta particle would produce a much smaller initial effect than a large alpha, but the avalanche would become so large that it would be impossible to tell what started it. Therefore, in the Geiger-Mueller region, it is possible to tell that radiation is present, but, it is not possible to determine the type of radiation. In the GM region, the number of ion pairs collected is always the same, no matter how many ion pairs were originally produced by the radiation.

If a second particle were to enter the detector during the avalanching period, it would not produce a pulse large enough to be detected. A second pulse could not be detected until the effects of the avalanche of secondary ions had been cleared out. The time during which the second pulse could not be detected is called dead time, and is equal to approximately 10^{-6} seconds. After the original pulse dies out, another full sized pulse can be produced. The time from the start of one full sized pulse until a second full sized pulse can begin is called the resolving time. A typical resolving time is a bout 10^{-4} seconds.

The dead time and the resolving time are really dependent on the time it takes for the positively charged cloud of ions to move toward the chamber walls. As has been mentioned, after the avalanching occurs, there are two smaller voltage potentials present, like two sub detectors, both operating well below the GM region. This means that any other particle of radiation interacting in either of the sub detectors will be affected by a much lower voltage, and the number of secondary ion pairs produced will be very small in comparison with the millions of ion pairs already produced. Thus, the new pulse would go undetected, and this would be the dead time.

As the positively charged cloud moves closer to the chamber walls, one large voltage potential and one smaller voltage potential sub detector are present. The larger voltage potential can cause enough gas amplification to produce a new pulse. However, the larger voltage is not yet as large as it should be, so the new pulse is not full sized, and it will not be detected by the outside electronics.

When the positively charged cloud reaches the chamber walls, there is only one large voltage
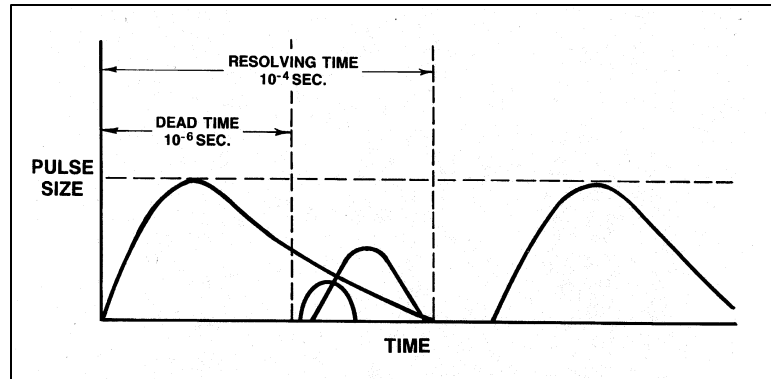
RP-3-4   Dead Time & Resolve Time

potential, and the detector is once again operating in the Geiger-Mueller region. Now a particle of radiation could cause a new avalanche of ions. Again, the time before a full sized pulse could be produced is the resolving time. Figure RP-3-4 represents resolving time and dead time in the Geiger-Mueller region.

Geiger-Mueller tubes are the detection instruments used in the Geiger-Mueller region. Most of these detectors use argon gas in the chamber because argon gas is easily ionized. However, there is a problem with argon gas. When the positive argon ion is collected on the electrode, it emits photons in the form of ultraviolet light. The photons can undergo a photoelectric effect interaction with the walls of the chamber, producing more electrons and starting the avalanche all over again.

To stop the continual avalanche, another gas, called a quenching gas, is mixed with the argon. The quenching gas is usually a halogen gas such as bromine or chlorine. As the positive argon ions move toward the negative electrode, they transfer their charge to the halogen gas molecules, and only the halogen gas molecules reach the electrode. The halogen gas molecules do not produce ultraviolet light. Instead, they disassociate when the energy transfer takes place at the wall of the detector. Later, the atoms recombine to form the original halogen gas molecules. Thus, the GM detector with a halogen quenching gas does not deteriorate with use.

2.5   CONTINUOUS DISCHARGE REGION

The last region in the six region curve is the continuous discharge region. In this region, the voltage across the electrodes is extremely high, and there is continuous arc across the

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electrodes. A detector should never be operated in this region. If it is, the detector could be damaged.

3.0   DETECTOR CHARACTERISTICS

Thus far three different types of gas-filled detectors the ionization chamber, the proportional counter, and the Geiger-Mueller tube have been discussed. Now the specific characteristics of these detectors will be compared and the following characteristics evaluated:

- Sensitivity to low levels of radiation
- Ability to differentiate between different types and energies of radiation
- Need to have an exact, constant voltage
- Use of the detector in areas of high radiation
- Use of the detector for measuring dose rates

To be able to compare the three detectors we need to assume that they are all of identical size. The Geiger-Mueller tube is the most sensitive to low radiation levels, because it has the largest pulse size. (Any radiation will produce an avalanche of ion pairs.) The next most sensitive detector is the proportional counter. Since some gas amplification is taking place, this region is sometimes called the gas amplification region. The least sensitive detector is the ionization chamber, where there is no gas amplification. In the ionization chamber, the pulse size (the number of ion pairs collected) is always equal to the number of ion pairs produced by the radiation.

This region is also called the ion collection region. A proportional counter and ion chamber have the ability to discriminate between different types and energies of radiation. The Geiger-Mueller chamber cannot do this. In the proportional counter and ion chamber the pulse size will vary for alpha and beta particles and it will also vary for different energies of radiation. If a GM tube were developed to detect alpha, beta, and gamma radiation, we would see that there is no difference in pulse size for the different types of radiation or different energies of radiation. Figure RP-3-5 illustrates the ability to differentiate between different types of radiation for all the regions.

Generally, the ionization chamber and proportional regions could be used for discriminating different types of radiation. This is especially true for laboratory instruments. Survey instruments used in the plant discriminate types of radiation, but, because of design considerations, discrimination is usually performed using an external shield on the detector.

Typical radiation measurement instruments used in the plant that use proportional detectors include:

- PNR-4 Neutron Detector
- Victoreen 497 RM-16

As can be seen by looking at the six region curve, if the voltage is varied in the ion chamber region, the pulse height will not vary significantly. The same holds true for the Geiger-Mueller region. The pulse height remains essentially constant over a relatively long plateau. This is not true in the proportional region, however. If the voltage is varied in the proportional region, the pulse height will vary proportionately. We can see, therefore, that a well regulated voltage supply is required for the proportional counter.

Ionization chambers and proportional counters can be used in high radiation areas and for dose rate measurements, but Geiger-Mueller tubes normally cannot. This is because the GM tube will not detect every pulse of radiation, due to the resolving time needed to clear away the avalanche of ion pairs. Interactions would be missed and the reading obtained could be much lower than what is actually present and the dose rate to which a person is exposed would be underestimated. Resolving time is not a problem with ionization chambers and proportional detectors, because avalanching does not occur. Some GM detectors have been designed with sophisticated external electronics suitable for high radiation levels and dose rate measurements, but the ionization chamber is generally the best type of instrument for these measurements.

Figure RP-3-5 is a review of the six region curve, with all the regions labeled. The ionization chamber region, the proportional region and the Geiger-Mueller region are the most important, because they are the regions in which detectors are operated.
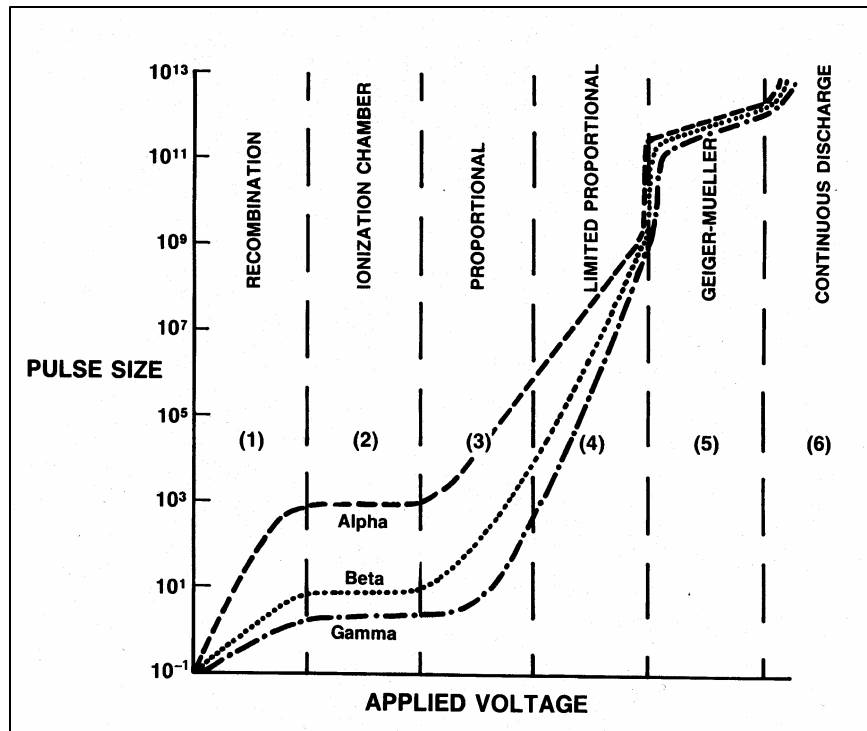
RP-3-5 Alpha, Beta, Gamma Six Region Curve

It is important to remember that in the ionization chamber region, the number of ion pairs collected is exactly equal to the number of ion pairs produced by the radiation. In the proportional region, the number of ion pairs collected is proportional to the number of ions pairs produced by radiation. At a given voltage, this proportionality is the same for all types and energies of radiation. In the Geiger-Mueller region, the number of ion pairs collected is the same because of the avalanching effect.

3.1   DETECTION AND PERSONNEL MONITORING

Thus far the three useful regions of the six region ion chamber curve have been discussed. The three regions: ion chamber, proportional counter, and Geiger-Mueller region all have detectors that are designed to operate in the various regions. Detectors are named by the region within which they operate. This section will explain six other types of radiation detection and measurement devices:

- Scintillation detectors
- Semi-conductors
- Neutron detectors
- Film badges
- Direct reading dosimeters
- Thermoluminescent dosimeters (TLDs)

Scintillation detectors and semi-conductors are usually found in radiochemistry or health physics counting labs in the plant. Neutron detectors can be portable, or can be at fixed locations in the reactor. Film badges, direct reading dosimeters, and thermoluminescent dosimeters (TLDs) are all personnel monitoring devices worn by personnel in the station. The direct reading dosimeter is a gamma sensitive device and indicates gamma whole body exposure. The film badge is sensitive to beta and gamma radiation and also registers whole body dose.

3.2   SCINTILLATION DETECTORS

If a material gives off light when radiation interacts with it, it is said to scintillate. The amount of light given off is proportional to the amount of incident radiation. This light can be measured and the information used to calculate the amount of radiation exposure.

Different types of scintillating material are used to detect different types of radiation. For example, a thin layer of zinc sulfide is generally used to detect alpha radiation; an anthracene crystal is used for beta; and a sodium iodide thallium activated crystal detects gamma. Scintillation detectors can exist in any physical state (i.e., solid, liquid, or gas), but the most common detectors are solid crystalline materials. The basic functioning of the detector is the same no matter what type of scintillation material is used.
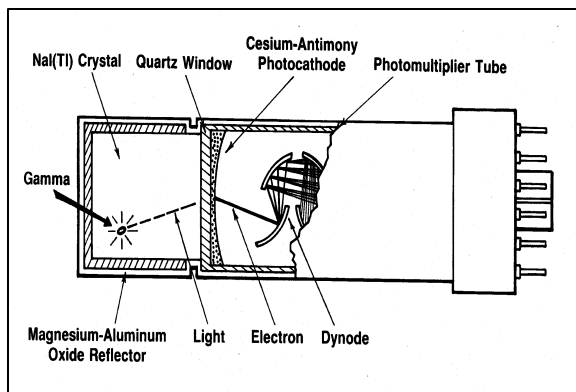
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Since scintillation materials have a higher density and higher effective atomic number, they present more target atoms for interaction with ionizing radiation than gas filled detectors. Scintillation detectors of a similar size as a gas filled detector will produce a greater number of excited electrons making them more sensitive to lower activity levels of the radiation being measured.

Gamma photons interact with the crystal in several ways to produce energetic electrons. The electrons ionize some of the atoms in the crystal. When molecules of sodium iodine (NaI) are ionized, the electron ejected is not energetic enough to be a free electron. The exciton, as it is called, leaves its original orbital position, but does not leave the atom itself. The energy of the exciton is eventually imparted to the activating material (thalium, in the case of a NaI (TI) crystal), raising certain atoms of the material to an excited state. These excited atoms then radiate this energy in the form of light. This entire interaction, from the time a gamma photon enters the crystal is until the light is emitted, takes place in a fraction of a microsecond. The crystal is usually surrounded with a diffuse reflection material to improve the light transmitting qualities of the crystal.

Crystals in the detector are canned in metal, usually aluminum, except for the end, which is attached to the photomultiplier tube. This end is enclosed by a glass or quartz window, which is optically connected to the photomultiplier tube either through direct contact, or through the use of a device referred to as a "light pipe" that helps to direct the emitted light to the photomultiplier tube. The crystal must be canned for two reasons:
External light must be prevented from entering the crystal.

Moisture must be kept out. Because the crystal is hygroscopic, it will absorb moisture from the atmosphere that would destroy the crystal.

Figure RP-3-6 shows a gamma scintillation detector. Like the other radiation detectors we have discussed, it has three basic components the detector, power source and a measuring device. The detector component consists of the scintillation material (in this case, a sodium iodide thallium activated crystal) and a photomultiplier tube with positively charged dynodes in it. At one end of the photomultiplier tube is a photocathode, and at the other end is an anode. The circuit is connected between the photocathode and the anode. If there is a flow of electrons between these two electrodes, there will be a current flow that can be measured on the measuring device.

RP-3-6 Gamma Scintillation Detector

When a gamma ray interacts with the scintillation material, visible light is given off. This visible light interacts with the photocathode, and electrons are emitted. These are the first two steps in the scintillation detection process. In the third step, the electrons are multiplied by 10^6 by the dynodes in the photomultiplier tube.

To illustrate the third step, let's follow one electron from the time it is emitted by the photocathode. The electron is attracted to the first positively charged dynode. When it strikes the dynode, more electrons (typically four) are emitted. The first dynode is shaped so that it directs the emitted electrons to the next dynode. The electrons are multiplied again by the second dynode and sent to the third dynode. The electron multiplication continues throughout all the dynodes in the photomultiplier tube. The result is a large flow of electrons striking the anode. Typically, each electron emitted from the photocathode will end up as about a million electrons striking the anode.

In the fourth step the anode collects the electrons. A measurable electrical current is the result. The current is measured by the measuring device.

The output of a scintillation detector is a pulse of electrons that is proportional to the energy of the original radiation interacting with the scintillating material. If the original radiation has more energy coming in, there will be more light emitted more electrons, and a larger pulse.

Scintillation detectors are extremely sensitive instruments. They are often used in plant laboratories where precise measurements are needed. They are also mounted on process systems in the plant to measure radiation levels in the liquids or gases flowing through the systems. Detectors used in this way are called process monitors and will be discussed later.

3.3   SEMI-CONDUCTOR DETECTION SYSTEMS

A semi-conductor detector crystal structure provides a greater number of atoms per unit volume. In the crystalline structure the electrons can exist in a valence band or a conduction band. The valence band electrons are bound to specific sites within the lattice structure. The conduction band electrons are free to move through the crystal structure. The addition of energy is required to move an electron from the valence band to the conduction band.

In a good conductor the energy gap between the valance band and the conduction band is very small, so electrons can easily move through the material (i.e., pass a current). In a good insulator, there is a large gap between the bands so that a large amount of energy is required to move an electron into the conduction band. A semi-conductor has a smaller band gap than that of insulator so that under certain conditions, electrons can be moved to the conduction band leaving behind a positive "hole" in the crystal structure.

Semi-conductor detectors are widely used in nuclear power stations electronic dosimeters, portable survey instruments in gamma spectroscopy systems used for isotopic analysis. Commonly used semi-conductor materials that measure radiation include Cadmium-Telluride, Silicon, High Purity Germanium (HPGe) and Lithium drifted Germanium (GeLi).

In order for a semi-conductor crystal to operate as a radiation detector, the crystal must be "depleted" or free of excess electrical charges. This depletion region can be formed either through the use of very high purity materials (HPGe), or by mixing or "drifting" a material with an excess of positive and negative impurities (GeLi).

When ionizing radiation interacts with the crystal in the depletion region, electron energy is raised to the conduction band leaving behind positive holes in the crystal structure. If a voltage is applied across the crystal, the electrons will be drawn to the anode and the holes will migrate to the cathode. The combination of electron and hole movement creates a current flow in the circuit, which results in a pulse.

The size of the pulse is directly proportional to the number of electrons collected, which is proportional to the energy deposited in the crystal by the incident radiation. The process is analogous to a gas filled detector in that the depletion region acts as a solid "fill gas", and the electron-hole pairs would be the equivalent of ion pairs.

Semi-conductor materials used for radiation detection require only a very small amount of energy to produce an electron-hole pair. This creates a big advantage over other detectors in that the pulses can provide a much better resolution of the incident gamma energy when used with a gamma spectroscopy system. Germanium detectors used in some gamma spectroscopy systems are operated at near liquid nitrogen temperature to prevent the creation of electron-hole pairs from the thermal energy available at room temperature.

3.4   NEUTRON DETECTION

Neutron detection using any of the detectors described so far, is not possible. This is because the neutron is not a charged particle or a photon. Since the neutron is a neutral particle, special detection methods are required.

Neutrons need to be detected for two reasons. First, we want to protect personnel and second, neutrons are the energy producers in the nuclear core. We need to know how many there are at any particular time in order to calculate power level.
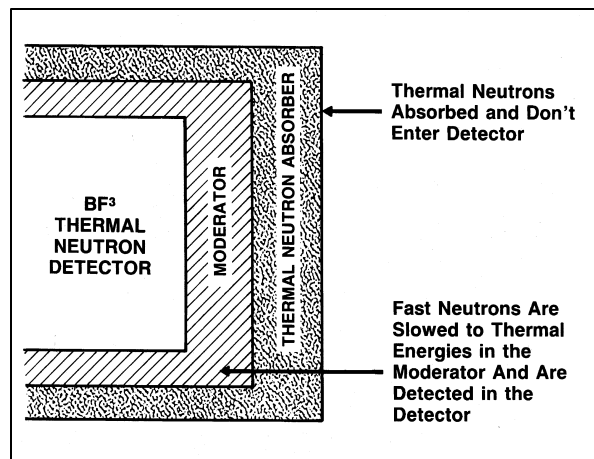
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Next, thermal neutron detection, fast neutron detection, and a method for detecting neutrons of several different energies will be discussed. Because neutrons do not produce ion pairs directly, all neutron detection methods must use some intermediate reaction to produce a particle that can cause ionization. A measure of the ion pairs produced by this particle is then used to indirectly measure the neutrons.

One method of detecting thermal neutrons uses the thermal neutron/boron-10 reaction to produce lithium-7 and an alpha particle. (In this induced nuclear reaction, the thermal neutron and the boron-10 are the reactants, and the lithium-7 and the alpha are the products.) The alpha then causes ionization, which can be detected. This reaction can be used in a gas-filled detector with either a boron lining or a gas that contains some boron trifluoride (BF-3). The thermal neutron interacts with the boron (which has a very large thermal neutron cross section) to produce an alpha. The alpha causes ionization in the gas, producing ion pairs that cause current flow in the circuit.

These gas-filled detectors are used in portable instruments to check for thermal neutron leakage around penetrations in the containment structure, and to measure neutron radiation levels to which personnel are exposed.

Another thermal neutron detector that is frequently used in the reactor is the fission chamber, which uses the fission reaction to detect thermal neutrons. In the fission chamber, one of the electrodes is coated with a fissile material, such as uranium-235. When a thermal neutron is absorbed by the U-235 nucleus, it usually fissions. The fission fragments are positively charged ions that have a lot of kinetic energy. As the fission fragments pass through matter, they cause ionization, which produces a measurable electrical current. The fission chamber is generally used in the reactor to measure levels of thermal neutrons, which is proportional to power level.

Two methods are also available for detecting fast neutrons. One method, as shown in Figure RP-3-7, slows the fast neutrons down to thermal energies and then use thermal neutron detection methods. This is done by enclosing a thermal neutron detector (such as a BF-3 detector) in a moderator shield (one with many hydrogen atoms in it, such as paraffin or polyethylene). When this type of detector is attached to a proportional counter, as in the PRN-4, it makes a very efficient and useful portable neutron
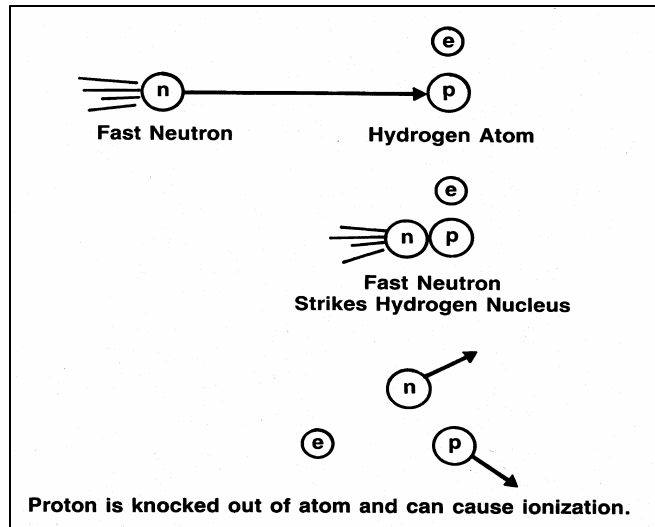

RP-3-7   Fast Neutron

detector. A good thermal neutron absorber, such as cadmium surrounds the moderator. When a thermal neutron approaches this detector, the cadmium shield absorbs it. A fast neutron, however, would go through the cadmium shield and lose its energy by interacting with the moderator that surrounds the detector.

After it loses its energy, the fast neutron becomes a thermal neutron, and can be measured in the thermal neutron detector. With this type of detector, thermal neutrons are weeded out and the remaining neutrons, the original fast neutrons, are measured.

Some neutron detection instruments can be used for both thermal neutron detection and fast neutron detection. In one position the detector is surrounded by a moderator and a thermal neutron absorber so only thermalized fast neutrons can reach the detector. When the thermal neutron detector is pulled out of its housing it can detect thermal neutrons. Since it is no longer surrounded by the moderator and the thermal neutron absorber.

A second method of fast neutron detection uses the (h, r) induced nuclear reaction to produce a charged particle in this case, a proton. The proton causes ionization, which can be detected. The particular reaction used in a neutron interaction with a hydrogen-1 nucleus (Figure RP-3-8). When a fast neutron is scattered by the nucleus it may impart enough energy to the nucleus which is a proton, to knock it away from the electron that orbits around it. This produces a free proton that can cause ionization in a detector.

Fast Neutron   **Hydrogen Atom**

Fast Neutron Strikes Hydrogen Nucleus

Proton is knocked out of atom and can cause ionization.

RP-3-8 Proton Recoil

The process is called proton recoil, because the proton recoils out of the hydrogen-1 atom. The hydrogen used for proton recoil fast neutron detection is usually contained in paraffin or polyethylene inside the detector itself. As we will see later, proton recoil is used in film badges to measure exposure from fast neutrons.

The last neutron detection method is foil activation. This method combines principles of activation and resonance absorption peak. When neutrons with energies equal to the resonance energy strike the foil, they are absorbed. Neutrons that are not at this resonance

energy go on through the foil. When neutrons are absorbed into the foil, they activate the absorbing nuclei. The foil activity can then be measured by a laboratory instrument, and the results can be used to calculate the number of neutrons with the resonant energy that were absorbed. If, instead of using one foil, we use several different foils, each with different resonance energy, we can determine the number of neutrons of different energies that passed through the foils. Some of the materials used for these foils are gold, silver and indium.

4.0   PERSONNEL MONITORING

We determine the rate of radiation exposure with units of counts per minute or mR per hour. For personnel exposure and radiation protection we are concerned with integrated dose. What is the total amount to which a person has been exposed? The measuring devices used are different from those already discussed. There are essentially three different types of integrated dose monitors including:

- Direct Reading Dosimeters
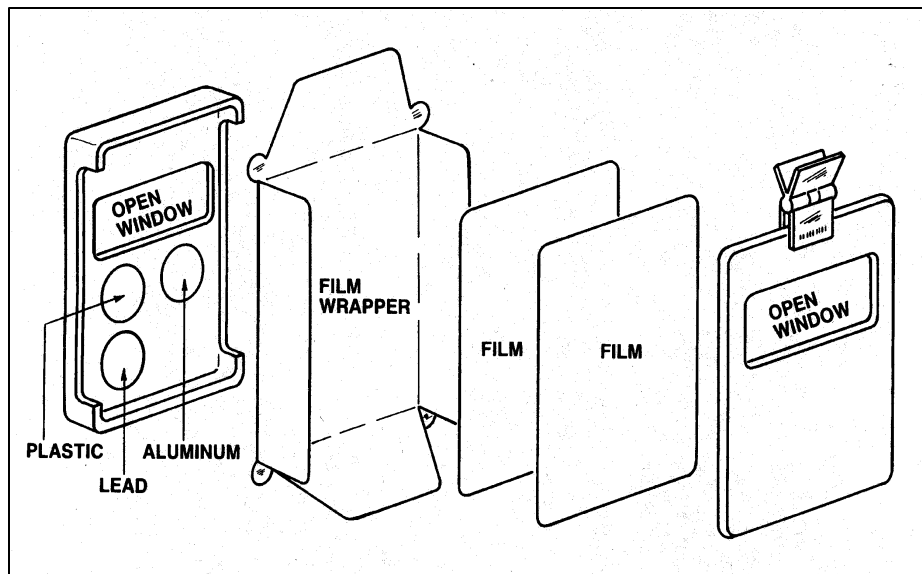- Film badges
- Thermoluminescent Dosimeters (TLDs)

4.1   FILM BADGES

The film badge is a beta/gamma sensitive device that measures total whole body dose. The badge itself is a small plastic holder that contains a photographic film packet. Inside the packet are two pieces of photographic film, tightly wrapped in a paper envelope to prevent light from exposing the film. One piece of film is sensitive to low radiation exposure levels and the other is sensitive to high exposure levels.

When radiation interacts with the film emulsion, it produces ions that chemically activate silver molecules in the emulsion. When the film is put into a developing solution, the chemically activated silver atoms are changed into elemental silver, which turns black. The degree of this blackness or its density is read on a machine called a densitometer and the reading is an indication of the beta and gamma dose.

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Figure RP-3-9 shows a film badge. The film badge holder has an open window that allows beta and gamma radiation to enter. This means that the blackness of the film (after it has been developed) in the area behind the window is a measure of the total beta and gamma dose. Most film badges have different inserts in other parts of the holder to shield out betas and lower energy gammas. For example, one part of the holder might have a plastic insert, another an aluminum insert, and still another a lead insert. After the film is developed, the blackness will vary behind the different inserts, depending on the ability of different energy gammas to penetrate them. This ability to penetrate is a measure of the incident photons energy, so the film badge can tell us what energy radiation we have been exposed to as well as how much of each energy radiation.

RP-3-9   Film Badge

Film badges should always be worn in a consistent location. Commonly, it will be specified that film badges are to be worn on the upper front trunk of the body. It could also be clipped to a shirt pocket or collar.

Special film badges for neutron exposure are issued to anyone who goes into an area where there is a possibility of being exposed to neutron radiation. The film used to detect fast neutrons generally contains a hydrogen emulsion, and the detection method used is proton recoil. The recoiling protons cause ionization as they move through the film emulsion. When the film is developed, there will be microscopic black tracks on it. By using a microscope and counting the number of tracks on the film, we can determine how many fast neutrons interacted with it.

4.2 THERMOLUMINESCENT DOSIMETERS

Many stations now use thermoluminescent dosimeters (TLDs) instead of film badges. This is because the TLD is not subject to the interpretation of the densitometer. It is a more modern device and lends itself to automated reading and record keeping. Externally, the TLD looks the same as a film badge but it may be slightly larger or smaller. Inside, it is quite different. Instead of film, the TLD contains a piece of thermoluminescent material. Thermoluminescent material is material that will give off light when heated in proportion to the amount of radiation it has been exposed to.

To understand how a detector chip measures radiation, a short review of electron energy levels is needed. As we know, electrons in a solid material prefer to be in their ground energy state. This is especially true for a crystalline material. If radiation imparts enough energy to one of these electrons, the electrons prefers to be in the ground state and will drop back to the ground state and emit the extra energy in the form of heat, X-rays, or light.

In TLD material, there is an in between state called a metastable state, which acts as an electron trap. As shown in Figure RP-3-10, when radiation interacts with the ground state electron, it jumps up and is trapped in the metastable state. It remains there until it gets enough energy to move up to the unstable state. This energy is supplied when the TLD chip is heated to a high enough temperature. Then the electron will drop back down to the ground state, and, because the TLD chip is a luminescent material, it will release its extra energy in the form of light.
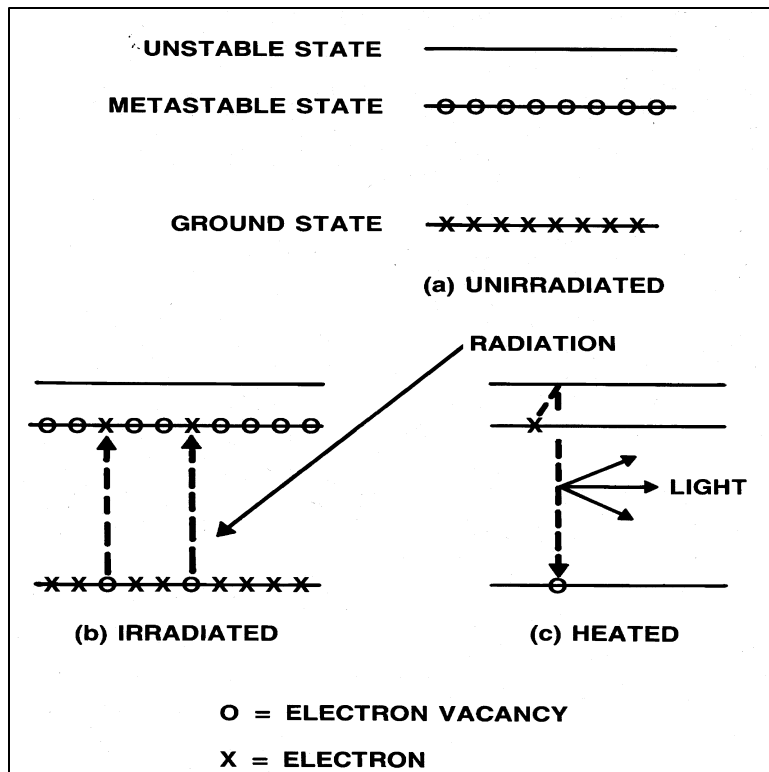

RP-3-10 Thermoluminescent Mechanisms

The total quantity of light emitted by electrons returning to the ground state is proportional to the number of electrons trapped in the metastable state. The number of electrons trapped in the metastable state is proportional to the amount of beta and gamma radiation that interacted with the material. This means that the amount of light emitted when the TLD is heated is proportional to the number of beta and gamma radiation interacting with the material.

As shown in Figure RP-3-11, the TLD reader consists of a heater and a photomultiplier tube like the ones used in scintillation detectors. When the TLD chip is heated, light from the chip is directed into the photomultiplier tube. In the photomultiplier tube, electrons are produced in the photocathode, multiplied across the dynodes, and finally collected on the anode. This then produces a pulse in the circuit that is proportional to the total amount of beta and gamma radiation absorbed by the TLD material.
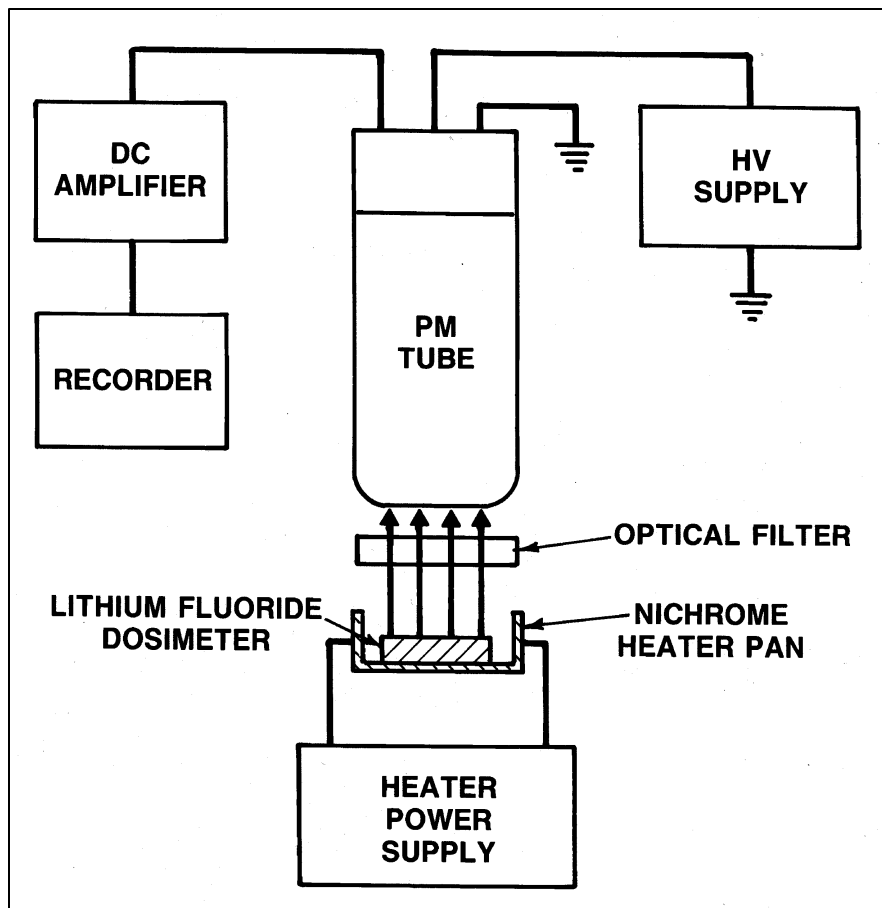
RP-3-11 Thermoluminescent Dosimeter

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There are several reasons for using TLDs instead of film badges. One reason is size TLD chips are so small that they can be taped to the fingers to measure exposure to the extremities without interfering with work. A second reason is sensitivity. The TLD is generally more sensitive than a film badge, more accurate in the low mR range, and able to provide a better overall indication of the total beta/gamma dose received.

A third reason is that the TLD chip can be reused after it is read. A fourth reason is that the TLD is not as sensitive to moisture as is the film badge, so data would not be lost if the TLD became wet. The only disadvantage to the TLD, is that it is relatively expensive to use.

4.3   DIRECT READING DOSIMETERS

Direct reading dosimeters allow you to determine how much gamma radiation you have been exposed to. Direct reading pocket ion chambers use a small capacitor, charged prior to use that is connected to glass fiber electroscope. This detector is mounted in a pen type housing that can be clipped to a pocket or lab coat. If the detector is exposed to ionizing radiation, a loss in charge potential of the chamber results. This loss of charge is indicated by a corresponding deflection of the glass fiber. The deflection can be viewed by means of a microscope built into the dosimeter. The amount of deflection and corresponding dose is indicated on a scale.

The movement on the fiber, then, is a measure of the amount of gamma radiation absorbed by the dosimeter.

In direct reading pocket dosimeters (Figure RP-3-12), a scale is placed so that the hairline on the scale is the movable fiber. As the fiber moves, the scale indicates the total amount of gamma radiation absorbed by the dosimeter. A microscope inside the dosimeter enables you to read the scale and see the total gamma dose received.
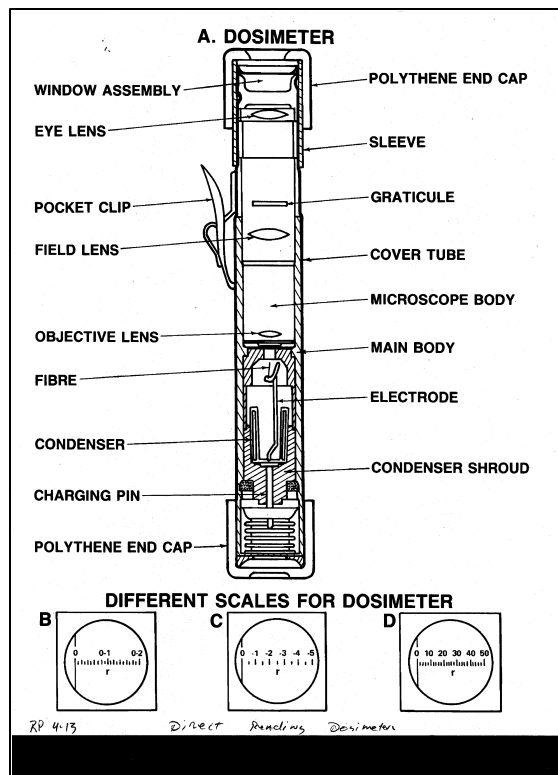
RP-3-12 Direct Reading Dosimeter

To reset the dosimeter, chargers are provided. These are usually located at station access points of convenience. To use a charger, place it on a firm level surface, preferably a table. Remove the cap that protects the charging terminal and place the end of the dosimeter in the charger. Gently press down in the dosimeter as you view the scale in the dosimeter. You will note that as you press down, a light is activated in the charger allowing you to see the scale. If you press down with approximately 10 pounds of force, the charging pin will make contact with the dosimeter charge contact and a voltage will be applied across the dosimeter. You can vary this voltage with the knob on the charger and when this is down you will note that you can move the hairline indicator up and down the scale of the dosimeter. Place the hairline slightly below the zero setting of the scale. It is normal for the setting to "jump-up" about 5 mR as you remove the dosimeter from the charger.

Because a direct reading dosimeter measures the whole-body gamma radiation dose, it should be worn in the major trunk area. When you are using a dosimeter, be careful not to bang or drop it. Typical errors and problems commonly found when the dosimeter reading is different than the actual dose include:

- Improper placement of the dosimeter on the body
- placing the dosimeter closer to the source of radiation than the TLD
- high heat and humidity conditions in the area of work and the quality factor of the radiation.
- Rough treatment may cause the electrode to discharge completely, sending the hairline all the way upscale.

The film badge, the direct reading dosimeter, and the TLD are normally worn in the major body region to give the best indication of whole-body dose. There are times, however, when these devices might be worn on other parts of the body. For example, a TLD might be moved to an arm or a leg if these protons of the body might receive more radiation than the trunk area. An additional device such as a finger ring might also be used to measure an extremity dose.

A finger ring contains either a piece of film or a TLD chip to measure absorbed dose from beta and gamma radiation. Special requirements are normally specified on the Radiation Work Permit for a particular job.

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5.0   PHYSICAL AND ELECTRONIC DISCRIMINATION

How can we differentiate between the different types and energies of radiation? If we think of the properties of the radiations discussed we could tell the difference between them by their ability to penetrate matter. We know for example, that a thin sheet of paper will shield alpha radiation. If we place a piece of paper over an alpha/beta sensitive detector and the reading decreases, we know that some of the radiation detected was alpha radiation. This is an example of one of the two types of discrimination, physical and electronic discrimination. Physical discrimination is possible using shields or different physical materials. Electronic discrimination uses electrical components.

Some instrument probes have built-in physical discrimination devices. Sliding windows are used to eliminate the beta component of beta/gamma sensitive ion chamber survey meters. Sliding aluminum or cadmium shields are used on Geiger-Mueller probes for the same reason. The film badge and TLD badge have built-in shields of copper, cadmium or lead to provide energy discrimination.

We could also physically discriminate using materials that are sensitive to only one type of radiation. The alpha scintillation probe is a good example of this with its thin layer of zinc sulfide. Electronic discrimination can be used for more precise discrimination between energy of detected radiation.

5.1   DETECTOR CHARACTERISTICS

Many terms have been expressed in this chapter about radiation detectors. We still need to discuss the activity that these instruments will detect. The best way to describe these terms is to define them. They are:

- Minimum Detectable Activity (MDA)
- Minimum Detectable Counts (MDC)
- Lower Limit of Detection (LLD).

MDA is the minimum activity present in a sample that may be detected by a particular instrument. We would like to see the value of MDA as low as practical. There are four methods available to reduce MDA values, which include:

1)   Collecting larger sample volumes.
2)   Reducing the background (another counting system or different area).
3)   Counting samples longer.

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    4)   Selecting a counting system with greater efficiency.

MDA is mathematically expressed as:

$$MDA(\mu Ci/ml) = \frac{MDC}{(V)(Eff)(Y)(A_b)(T_r)(M)(2.22E+6)(e^{-t})}$$

Where: cpm_b = background counts per minute

t_b	=	background counting time, minutes.
V	=	volume of sample, cc
Eff	=	counter efficiency (converts cpm to dpm)
Y	=	chemical yield (if applicable).
A_b	=	abundance
Tr	=	resolving time correction (if applicable) compute compensation will normally account for this correction.
M	=	self absorption correction (if applicable), only significant in counting charcoals.
e	=	decay constant based on the half-life of sample activity (if applicable), only isotopic specific.
t	=	elapsed time from time sampled to time counted (if applicable).
2.22E+6	=	converts dpm to µCi.

Lower Limit of Detection (LLD) is a term which is only related to the detector. LLD is defined as "the smallest amount of activity that will yield a net count for which there is a confidence at a predetermined level that activity is present". LLD is an estimate of the detecting capabilities of a counting system and depends on:

- Instrument parameters.
- Total background counts detected.

Minimum Detectable Counts (MDC) is the LLD defined in terms of a count rate since the background counts is time dependent. MDC is that count rate which indicates the presence of activity with a probability of x and with only a (1 - x) probability of falsely concluding its presence.

- A 90% probability of detection, 10% probability of false detection is deemed a 90% confidence level.

- Confidence level is at the discretion of the operator.

MDC is mathematically expressed as:

$$\text{MDC} = 2m \sqrt{R_2/t_s + R_b/t_b}$$

Where: MDC   =   minimum detectable counts

R_b =   the background count rate

t_b =   the background counting time

t_s =   the sample counting time

m   =   a constant which depends on the confidence level;

is used to calculate the minimum detectable count rate.

6.0   SUMMARY

The human body cannot detect radiation directly. We would eventually learn that we were exposed to radiation but only after the body had suffered some injury. Radiation detection by other means is therefore vitally important for any radiation protection program.

We have learned in this chapter how various radiation detection instruments work, their characteristics and operational limitations. You should know how you will be monitored for radiation exposure and how we tell what types of radiation you have been exposed to.