

RADIATION MONITORING

Jyoti D, Assistant Professor

10.1. INTRODUCTION

Radiation detection and monitoring are fundamental components of radiation safety, particularly in environments where ionizing radiation is used or encountered, such as hospitals, nuclear facilities, research laboratories, and industrial sites. The primary goal of radiation safety is to protect individuals and the environment from the harmful effects of ionizing radiation while enabling its beneficial use. Effective detection and monitoring systems allow for the identification, quantification, and control of radiation exposure, ensuring that it remains within established safety limits. In practice, various types of radiation detectors are employed to monitor radiation levels, including Geiger-Müller counters, ionization chambers, scintillation detectors, and dosimeters. These instruments are used to measure different types of radiation—alpha, beta, gamma, and neutron—and are selected based on the specific application and type of radiation present. Personal dosimeters, such as thermoluminescent dosimeters (TLDs) or electronic personal dosimeters (EPDs), are commonly worn by workers to track cumulative radiation exposure over time, ensuring it does not exceed regulatory dose limits. Routine monitoring also includes area surveillance in workspaces where radiation sources are present. Fixed or portable survey meters are used to assess ambient radiation levels, detect contamination, and evaluate shielding effectiveness. Continuous monitoring systems may also be installed in high-risk areas to provide real-time data and alarms if radiation levels exceed pre-set thresholds. Radiation detection and monitoring are critical for implementing the ALARA (As Low As Reasonably Achievable) principle, which is a cornerstone of radiation protection. By providing accurate and timely data, these systems enable the implementation of protective measures, such as time, distance, and shielding strategies, to reduce exposure. Ultimately, the integration of reliable radiation detection and monitoring ensures a safe working environment, supports regulatory compliance, and promotes a culture of safety in all radiation-related practices [1].

Radiation Monitoring

Radiation monitoring is a vital component of radiation protection and safety, involving the use of specialized equipment to detect, measure, and assess the presence and intensity of ionizing radiation in various environments. The primary goal is to ensure that radiation levels remain within safe limits for workers, patients, and the public, particularly in settings such as hospitals, nuclear facilities, research laboratories, and industrial plants. There are two main types of radiation monitoring: personal monitoring and area or environmental monitoring, each utilizing different types of equipment based on the purpose and type of radiation involved. Personal radiation monitoring devices are worn by individuals who may be exposed to radiation as part of their job. Common examples include thermoluminescent dosimeters (TLDs), which measure accumulated radiation dose over time using crystals that emit light when heated, and optically stimulated luminescence (OSL) dosimeters, which use light to release stored radiation energy, allowing for accurate and repeatable dose readings. Film badges, though older, also serve a

similar purpose using photographic film. More advanced devices such as electronic personal dosimeters (EPDs) provide real-time dose readings and can alert the wearer when dose limits are exceeded, making them highly effective in high-risk environments ^[2]. Area and environmental monitoring equipment is used to detect and measure radiation levels in specific locations. Geiger-Müller (GM) counters are among the most widely used instruments for detecting beta and gamma radiation and are known for their audible clicks indicating radiation presence.

Ionization chambers are employed for measuring high levels of radiation with precision, making them suitable for radiation surveys and equipment calibration. Scintillation detectors, which use special materials that emit light when exposed to radiation, offer high sensitivity and are particularly useful for detecting low levels of radiation. Neutron detectors are specialized instruments designed for neutron radiation detection, often found in nuclear power and research facilities. Additionally, contamination monitors are used to detect radioactive particles on surfaces, clothing, or equipment, while environmental radiation monitors continuously track background radiation levels in and around facilities ^[3]. Radiation dosimeters, whether used for personnel or area monitoring, possess specific properties that make them suitable for accurately measuring exposure to ionizing radiation and ensuring safety in various environments. For personnel monitoring, the dosimeter must be lightweight, portable, and comfortable to wear continuously over long working hours. It should be capable of accurately measuring accumulated doses over time and be sensitive to the types of radiation commonly encountered in the workplace, such as gamma rays, X-rays, and beta particles. Key properties include high sensitivity, stability over time, the ability to record low doses accurately, and resistance to environmental influences such as heat, humidity, and light. For example, thermoluminescent dosimeters (TLDs) and optically stimulated luminescence (OSL) dosimeters are designed to be worn on the body and can reliably store dose information until they are read out. Electronic personal dosimeters (EPDs), in contrast, offer real-time monitoring, dose alarms, and digital data storage, providing immediate feedback to the wearer and enhancing safety, especially in high-risk or high-radiation areas.

For area monitoring, dosimeters and radiation detection instruments must possess different properties tailored to their environmental applications. These include broader range capabilities, higher durability, and continuous or real-time data collection features. Instruments such as Geiger-Müller counters, ionization chambers, and scintillation detectors used for area monitoring must be capable of detecting various radiation types and intensities across large or complex spaces. Their design must ensure reliability in different environmental conditions and be capable of long-term operation without loss of accuracy. Area monitoring devices often have features such as visual or audible alarms, data logging capabilities, and integration with remote monitoring systems for centralized safety management. They are generally more robust and may be either portable or fixed in strategic locations to continuously assess ambient radiation levels or detect contamination.

❖ Some key definition

- **Ionization:** Ionization is the fundamental physical effect of radiation. When high-energy radiation interacts with atoms or molecules, it can eject electrons, resulting in the formation of positive ions and free electrons. This process is critical in radiation detection, where the generated ions produce measurable electrical signals. Ionization is also responsible for initiating chemical and biological changes. It occurs in gases, liquids, and solids and is the basis for devices such as ionization chambers, Geiger-Müller counters, and proportional counters. In living tissues, ionization leads to the formation of reactive species, which can damage cellular structures and DNA, contributing to biological effects.
- **Luminescence:** Luminescence refers to the emission of light by a substance after it absorbs radiation. When ionizing radiation excites atoms in a luminescent material, electrons move to higher energy states. As they return to their original states, energy is released in the form of visible or ultraviolet light. There are two main types: fluorescence (light is emitted immediately) and phosphorescence (light is released slowly over time). This property is harnessed in scintillation detectors, commonly used in nuclear medicine and radiation monitoring. Luminescent materials help convert radiation into light signals that can be measured, allowing for precise radiation detection and imaging.

- **Photographic Effect:** The photographic effect of radiation involves the darkening of photographic film when exposed to ionizing radiation, such as X-rays or gamma rays. Silver halide crystals in the emulsion of photographic film undergo a chemical change when hit by radiation. Upon development, these altered crystals appear as darkened areas, forming a visible image that reflects the radiation exposure pattern. This principle was historically used in radiographic imaging (e.g., X-rays) and film badges for radiation dosimetry. While largely replaced by digital systems today, the photographic effect laid the foundation for modern imaging and radiation monitoring technologies in medicine and industry.
- **Thermo-luminescence:** Thermo-luminescence is a phenomenon where certain materials emit light when heated, after having absorbed energy from previous exposure to radiation. During exposure, electrons become trapped in the crystal lattice of thermoluminescent materials like lithium fluoride. When the material is later heated, the trapped electrons are released and return to their normal state, emitting light in the process. The intensity of the emitted light is directly proportional to the absorbed radiation dose. This property is widely used in thermoluminescent dosimeters (TLDs) to monitor occupational radiation exposure in medical, nuclear, and industrial environments, offering a reliable and cumulative measure of dose.
- **Chemical Effect:** The chemical effect of radiation refers to changes in chemical composition and structure caused by ionizing radiation. Radiation can break molecular bonds, create free radicals, and initiate new chemical reactions. These effects are used in various fields, such as food irradiation (to destroy bacteria and extend shelf life), radiation sterilization (to disinfect medical tools), and polymer modification (to enhance material properties). For example, water exposed to radiation breaks down into hydrogen and oxygen gases. In chemical dosimetry, radiation-induced colour changes in specific chemicals are measured to determine dose levels. Chemical effects are crucial in both practical applications and radiation damage studies.
- **Biological Effect:** Biological effects of radiation result from its interaction with living cells, primarily through ionization of water and organic molecules. This leads to the formation of free radicals, which can damage cellular components such as DNA, proteins, and membranes. The effects are categorized as deterministic (e.g., radiation burns, tissue damage—dependent on dose) or stochastic (e.g., cancer, genetic mutations—probability increases with dose). Radiation therapy uses these effects to target and kill cancer cells, while radiation protection aims to minimize harmful exposure. Biological effects depend on factors such as radiation type, dose, exposure time, and the sensitivity of the affected tissue.

10.2. PERSONNEL RADIATION MONITORING

Personnel radiation monitoring is a crucial aspect of radiation safety designed to measure and control the exposure of individuals working in radiation-prone environments. This monitoring ensures that occupational exposure remains within permissible limits set by regulatory bodies such as the International Atomic Energy Agency (IAEA) and the Occupational Safety and Health Administration (OSHA). It is primarily used in industries where workers are routinely exposed to ionizing radiation, such as nuclear power plants, medical imaging and radiotherapy centres, research laboratories, and industrial radiography. The primary objective of personnel radiation monitoring is to protect workers from harmful radiation effects, prevent overexposure, and ensure compliance with radiation safety regulations. Several methods and devices are used for personnel radiation monitoring. One of the most common methods is the use of dosimeters, which measure an individual's cumulative radiation dose over time. Thermoluminescent Dosimeters (TLDs) and Optically Stimulated Luminescence (OSL) Dosimeters are widely used for their accuracy and reliability in recording radiation exposure. Film Badges, though older in technology, are still used in some settings to assess cumulative dose exposure through changes in film opacity. Electronic Personal Dosimeters (EPDs) provide real-time radiation exposure readings, allowing immediate corrective actions in case of high exposure. Additionally, Pocket Ionization Chambers are used for on-the-spot radiation dose assessments.

Importance of Personnel Radiation Monitoring: Personnel radiation monitoring plays a critical role in ensuring the safety and well-being of workers exposed to ionizing radiation in various industries. It is essential in nuclear power plants, medical facilities, research laboratories, industrial radiography, and any workplace where

radioactive materials or radiation-emitting equipment are used. The primary goal of personnel radiation monitoring is to measure and control individual radiation exposure, ensuring that it remains within the permissible limits set by regulatory authorities such as the International Atomic Energy Agency (IAEA), the Environmental Protection Agency (EPA), and the Occupational Safety and Health Administration (OSHA). By continuously monitoring radiation exposure, potential risks can be identified and mitigated, preventing long-term health effects such as cancer, radiation burns, and genetic mutations^[4]. One of the key benefits of personnel radiation monitoring is its ability to provide early detection of overexposure. Continuous tracking of radiation dose levels allows workers and safety officers to take immediate action in case of excessive exposure, such as adjusting work schedules, enhancing protective measures, or even temporary removal from radiation-prone areas. Additionally, monitoring helps in ensuring compliance with safety regulations, which is mandatory for organizations handling radioactive materials. Failure to comply with radiation safety standards can lead to legal consequences, fines, and operational shutdowns. Personnel radiation monitoring also plays a vital role in long-term health surveillance. By maintaining detailed records of radiation exposure, medical professionals can assess cumulative doses received by workers over time. This data is crucial for diagnosing radiation-related illnesses at an early stage and providing necessary medical interventions. Moreover, it aids in radiation risk assessment and management, allowing industries to improve safety protocols and implement better shielding, protective gear, and training programs.

Table: 10.1. Importance of Personnel Radiation Monitoring

Importance	Description
Early Detection of Overexposure	Allows immediate identification of excessive radiation exposure, enabling corrective actions such as work schedule adjustments and enhanced protective measures.
Regulatory Compliance	Ensures adherence to safety guidelines set by agencies like the IAEA, EPA, and OSHA, preventing legal consequences and operational shutdowns.
Long-Term Health Surveillance	Maintains exposure records to monitor cumulative doses, aiding in early diagnosis and medical intervention for radiation-related illnesses.
Radiation Risk Assessment and Management	Helps industries improve safety measures, such as shielding, protective gear, and training programs, to minimize radiation exposure risks.
Emergency Preparedness and Response	Assists in assessing individual radiation exposure during nuclear incidents, guiding evacuation procedures and medical treatments.
Occupational Safety Research	Provides valuable data for scientists and regulatory bodies to refine exposure limits and develop improved radiation protection strategies.
Workplace Safety Enhancement	Contributes to creating a safer work environment by identifying and mitigating potential radiation hazards.

10.2.1. Thermo-luminescent Dosimeters (TLDs)

Thermo-luminescent Dosimeters (TLDs) are widely used devices in radiation protection to measure an individual's exposure to ionizing radiation. TLDs are an essential tool in personal dosimetry, environmental monitoring, and in medical, industrial, and research facilities where radiation exposure is a concern. It provides accurate, reliable measurements of radiation doses, and offer several advantages over other types of dosimeters. Below is a detailed explanation of how TLDs work, their components, applications, and benefits. The basic principle behind TLDs is based on the phenomenon of thermos-luminescence, where certain materials emit light when they are heated after being exposed to ionizing radiation. This light emission is proportional to the amount of radiation absorbed by the material, allowing it to be used as a measure of radiation dose^[5].

- **Material:** The most common materials used in TLDs are lithium fluoride (LiF), calcium fluoride (CaF₂), and magnesium tungstate (MgWO₄). These materials have the property of trapping electrons in their crystal lattice when exposed to ionizing radiation. These trapped electrons remain in a metastable state for a period of time.
- **Exposure:** When TLDs are exposed to ionizing radiation, such as gamma rays, X-rays, or beta particles, the energy from the radiation excites electrons within the crystal lattice of the TLD material. This energy causes the electrons to jump to higher energy states, leaving behind "electron traps" in the crystal.

- **Heating and Light Emission:** After the TLD has been exposed to radiation, it is heated in a TLD reader device. The heat provides enough energy to release the trapped electrons from their "traps," causing them to return to their ground state. As the electrons return to their original energy level, they release energy in the form of light. The amount of light emitted is proportional to the amount of radiation the TLD has been exposed to.
- **Measurement:** The light emitted by the TLD is collected by a photomultiplier tube and converted into an electrical signal. The intensity of the light is directly related to the amount of radiation exposure, and it is quantified to determine the dose received.



Fig: 10.1. TLD Badges

Table: 10.2. Ideal Features of a Thermo-Luminescent Dosimeter (TLD) Badge

Feature	Description	Benefit
High Sensitivity	The TLD badge should detect low levels of ionizing radiation.	Ensures even small radiation doses are measured, important for monitoring workers in environments with low but consistent exposure.
Accurate and Precise Readings	Provides reproducible and precise measurements of radiation doses.	Ensures correct exposure data for safety compliance and worker health monitoring.
Energy Discrimination	Ability to distinguish between different radiation types (X-rays, gamma rays, beta particles) and energies.	Allows for more detailed assessments of radiation exposure, helping to evaluate specific risks from different radiation sources.
Long-Term Stability	The material in the TLD should maintain its ability to record and preserve exposure data over time.	Maintains accurate radiation exposure records, crucial for long-term health monitoring and compliance with safety standards.
Reusability	The TLD badge can be reused after being reset through heating.	Cost-effective as badges can be used multiple times without the need for replacements.
Small, Lightweight, and Comfortable	Compact and ergonomic design for easy wear on the body without discomfort.	Ensures that workers can wear the badge throughout the day without interference with daily activities, encouraging continuous use.
Minimal Environmental Interference	Resistant to temperature fluctuations, humidity, and pressure.	Ensures reliable readings even in challenging work environments like medical, research, or nuclear settings.
Easy to Read and Interpret	Simple and accurate reading of radiation dose using a TLD reader.	Allows quick and easy assessment of exposure levels by radiation safety officers or personnel.

Compliance with Regulatory Standards	Adheres to national and international radiation safety standards (ICRP, NCRP, OSHA, etc.).	Ensures the badge meets safety requirements and can be used for official radiation monitoring and audits.
Durability and Protection	The TLD badge is housed in a durable casing to protect the thermoluminescent material.	Protects the TLD from physical damage, ensuring accurate readings and badge functionality.
Cost-Effectiveness	Provides a balance between affordability and performance.	Ensures widespread use in workplaces without compromising on quality or safety.
Quick Turnaround Time	Allows for rapid processing of radiation exposure data after reading.	Ensures quick updates to exposure records, enabling timely adjustments to safety protocols or work practices if necessary.

Construction of TLD Badge: The construction of a Thermo-Luminescent Dosimeter (TLD) badge involves several key components that work together to accurately measure an individual's exposure to ionizing radiation. The primary purpose of the TLD badge is to absorb and store the energy from ionizing radiation, which can later be read to determine the radiation dose received. Below is a detailed description of the various components involved in the construction of a TLD badge.

- **TLD Card (Thermo-luminescent Crystal):** At the heart of the TLD badge is the thermoluminescent material, typically a crystalline substance such as lithium fluoride (LiF). This material is chosen because it has excellent properties for trapping energy when exposed to ionizing radiation. Other materials, such as calcium fluoride (CaF₂) or magnesium tungstate (MgWO₄), can also be used, but LiF is most commonly used because of its high sensitivity and ability to store radiation energy for extended periods. The TLD material is usually processed into small chips, tablets, or pellets and serves as the active element that absorbs radiation. The crystals are usually doped with small amounts of impurities (such as magnesium or titanium) to enhance their ability to trap the radiation-induced electrons and hold them in a metastable state until they are later released during the readout process.
- **Housing/Container:** The TLD material is encased in a protective housing or container. This housing is typically made of lightweight and durable materials, such as plastic or metal, to shield the TLD material from physical damage and environmental factors like moisture or contamination that could affect the results. The housing is designed to be small, portable, and comfortable for the wearer, as the badge is usually worn on the body, typically at the chest or waist for personal dosimetry. The container also has a specific design to ensure the TLD material is in the correct orientation relative to the radiation source during exposure. The badge housing is often transparent or has small openings to allow radiation to reach the TLD material.
- **Filter Layers:** Some TLD badges incorporate filter layers to distinguish between different types of radiation or to provide more detailed information about the energy levels of the radiation. These filters are made from materials such as aluminum or copper, which selectively attenuate certain types of radiation. For example, a filter made of aluminum can reduce the amount of low-energy X-rays that reach the TLD material, helping to separate the dose from low-energy X-rays from higher-energy gamma rays or beta particles. Filters are often included in the badge to help determine the energy spectrum of the incident radiation and to obtain more accurate dosimetry data by distinguishing between different radiation types (such as alpha, beta, and gamma radiation).
- **Light-tight Envelope:** The TLD material and its protective housing are placed inside a light-tight envelope to prevent any ambient light from interfering with the measurement of the thermoluminescence. Since the TLD material stores energy in the form of trapped electrons, exposure to light before the dosimeter is read could potentially release some of the stored energy prematurely, leading to inaccurate dose readings. The light-tight envelope ensures that only the heat generated by the TLD reader can stimulate the emission of light during the readout process, preserving the integrity of the dose measurement.
- **Identification Label:** Each TLD badge is often marked with a unique identification number and may include the wearer's information (such as name or ID number). This is important for record-keeping and ensuring that the radiation exposure readings are correctly attributed to the right individual. The

identification label may also include the badge's issuance and expiration dates and other tracking information that allows the dosimeter to be monitored throughout its use.

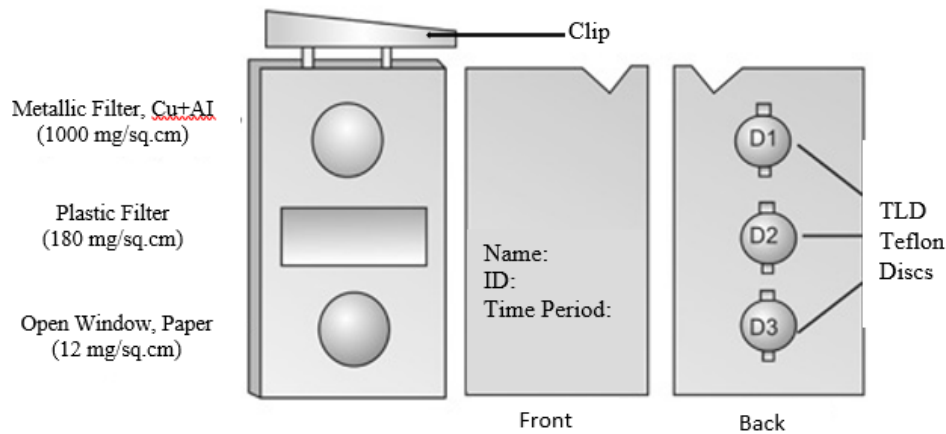


Fig: 10.2. Components of TLD Badge

- **Clip or Attachment Mechanism:** To allow the TLD badge to be easily worn by individuals in radiation environments, the badge is typically equipped with a clip or pin that can be attached to the individual's clothing. The clip is usually made of plastic or metal, and it ensures the badge remains securely attached to the person's body, typically at the chest or waist. This placement is critical because it ensures that the badge is exposed to radiation in the same way the person is exposed. In some cases, TLD badges can also be worn on a badge holder or be attached to a radiation protection suit, depending on the specific monitoring needs.
- **Protective Outer Layer:** To further enhance the durability of the TLD badge and protect the sensitive components inside, an additional protective outer layer is often added. This layer can be made of materials like plastic, which protects the TLD crystals from physical damage, dust, and moisture. It also provides resistance to environmental conditions that could affect the functionality of the badge. The outer layer may be designed to be lightweight and ergonomically shaped to ensure comfort for the wearer, while still maintaining its protective function.

Types of TLD Badges: Thermo-luminescent Dosimeter (TLD) badges are essential tools for monitoring radiation exposure in various occupational settings. These badges come in different types, each designed to be worn on specific parts of the body depending on the nature of the radiation exposure and the area of concern.

- **Finger TLD Badge:** One common type is the finger TLD badge, which is designed to monitor radiation exposure to the hands. This is particularly important for workers who handle radioactive materials or operate radiotherapy equipment, as hands are often exposed to higher doses of radiation. Finger TLD badges are typically small, lightweight, and worn as rings or straps around the fingers. They provide accurate readings of localized radiation exposure to the hands, helping ensure that workers are not exposed to harmful radiation levels.
- **Chest TLD Badge:** Another commonly used TLD badge is the chest TLD badge, which serves as a personal dosimeter worn on the chest area. These badges are designed to measure the total body radiation dose and are typically worn on the front of the clothing. The chest TLD badge is ideal for general radiation monitoring, as it provides a cumulative dose measurement that reflects the exposure of the torso. These badges are widely used in healthcare environments, such as hospitals and clinics, where workers might be exposed to radiation during procedures like radiology or nuclear medicine ^[6].
- **Waist TLD badge:** It is similar in design to chest badges but are worn around the waist. These are used to monitor radiation exposure to the lower body, especially in situations where radiation exposure may be unevenly distributed or localized to the lower torso. Waist TLD badges complement chest badges and

provide a more comprehensive assessment of radiation exposure. They are typically used in environments where workers are at risk of exposure to radiation from different angles or sources.

- **Neck TLD Badge:** Some workers, particularly in medical settings, might need neck TLD badges. These badges are worn around the neck using a lanyard or strap and monitor radiation exposure to the head and neck area. While less common than chest or waist badges, neck TLD badges are useful for assessing radiation exposure in areas where the head or neck is at higher risk of radiation, such as during certain radiological procedures ^[7].
- **Environmental TLD badge:** It used to monitor radiation levels in a specific area, rather than on an individual. These badges are placed in locations such as around nuclear power plants, laboratories, or radiation therapy departments, to assess the ambient radiation levels over time. Environmental TLD badges help ensure that radiation levels in the surrounding environment are within safe limits for both workers and the general public. Each type of TLD badge is designed to provide specific radiation exposure data, ensuring that workers and environments are adequately monitored for safety. By choosing the appropriate badge based on the area of the body most likely to be exposed to radiation, employers can ensure that radiation exposure is accurately measured and that necessary precautions are taken to protect workers from overexposure.

Table: 10.3. Advantages, Disadvantages, and Limitations of TLD Badges

Category	Feature	Description
Advantages	Accurate Dosimetry	TLD badges provide precise measurements of radiation exposure, essential in radiology. They record accumulated exposure, ensuring professionals don't exceed safety limits.
	Reusability	TLD badges can be reused multiple times (Quarterly). After analysis in a lab, they provide exposure data over a set period, making them cost-effective.
	Sensitivity to Different Radiation Types	TLD badges are sensitive to various radiation types, including X-rays and gamma rays, commonly encountered in radiology, making them versatile for diverse procedures.
Disadvantages	Time-Consuming Analysis	TLD badges require lab analysis to obtain radiation readings, leading to delays in obtaining results. Immediate feedback is unavailable, which can be a disadvantage.
	No Real-Time Monitoring	TLD badges do not provide real-time radiation readings, unlike electronic dosimeters, which means there is no immediate alert in case of high radiation exposure.
	Sensitive to Handling	Improper handling of TLD badges (e.g., exposure to light, heat, or mechanical stress) can result in inaccurate readings, compromising safety monitoring.
Limitations	Single Measurement Point	TLD badges measure cumulative exposure, but they do not indicate when or where the exposure occurred, limiting the understanding of specific radiation doses over time.
	Limited Detection of Low Doses	TLD badges are less sensitive to very low radiation doses, which could be a limitation in environments where low levels of radiation are frequent but still need monitoring.
	Calibration and Maintenance	TLD badges require periodic calibration to ensure accurate readings. Improper calibration or failure to maintain them can lead to incorrect readings, affecting safety.

Care and Maintenance of TLD Badge: The care and maintenance of a TLD (Thermo-luminescent Dosimeter) badge are crucial to ensure accurate radiation dose measurements and to prolong the lifespan of the dosimeter. Proper handling and storage can prevent inaccuracies in radiation readings and ensure the safety of individuals who are monitored for exposure. Below are some key points to consider when caring for and maintaining a TLD badge:

Table: 10.4. Key points on Handling, Use, and Care of TLD Badges

Category	Feature	Description
Handling and Use	Minimize Exposure to Light	TLD badges should be kept away from light sources, especially sunlight, to prevent partial activation of the thermoluminescent crystals, leading to inaccurate readings.
	Avoid Extreme Temperatures	Avoid exposing TLD badges to extreme temperatures (high or low). This can affect the accuracy of readings. Store and wear badges within the manufacturer's recommended temperature range.
	Avoid Physical Damage	Handle TLD badges gently as they contain sensitive crystals and electronics. Dropping or applying excessive pressure can damage the badge and cause faulty readings.
	Do Not Expose to Harsh Chemicals	TLD badges should not be exposed to chemicals or solvents that could damage their housing or internal components. Keeping the badge clean and free from contaminants ensures accurate measurements.
Storage	Store in a Dry, Cool Place	When not in use, store the TLD badge in a cool, dry location, away from radiation sources or light. A protective storage container is recommended.
	Avoid Storing Near Radiation Sources	Do not store TLD badges near radiation sources. Even low radiation levels can activate the thermoluminescent crystals, leading to inaccurate readings during later analysis.
	Storage Case	Store the TLD badge in a light-tight, protective case to prevent exposure to light and physical damage.
Regular Calibration	Periodic Calibration	TLD badges need periodic calibration to ensure accurate radiation dose measurements. Calibration is typically done by the manufacturer or a certified service provider.
	Calibration Records	Maintain a log of calibration dates and ensure recalibration is done at recommended intervals to maintain the dosimeter's accuracy and reliability.
Transportation	Proper Handling During Transport	Handle TLD badges carefully during transport. Place them in protective, light-tight cases and avoid temperature extremes.
	Avoid Interference with Other Dosimeters	When transporting multiple TLD badges, keep them separate to prevent accidental exposure or contamination, which could alter the readings.

Disposal	Proper Disposal	Once used and analyzed, dispose of TLD badges according to local regulations or return them to the service provider for proper disposal.
Avoiding Cross-Contamination	Avoid Storage Near Personal Items	Do not store TLD badges near personal items like phones or wallets that could cause unintended radiation exposure and interfere with the accuracy of the readings.
Preventing Interference from Other Sources	Avoid High-Powered Electronics	Although TLD badges are resistant to electromagnetic interference, it's still best to avoid placing them near high-powered electronic equipment to ensure accuracy.

10.2.2. Pocket Dosimeter

A pocket dosimeter is a compact, portable instrument designed for real-time monitoring of individual exposure to ionizing radiation, widely utilized in radiology, nuclear medicine, and other radiation-prone environments. It is especially valuable for personnel requiring immediate dose feedback, such as radiologists, radiologic technologists, and radiation safety officers. These devices provide on-the-spot measurements of radiation dose, helping to ensure that occupational exposure remains within safe limits. The operation of a pocket dosimeter is based on its ability to detect and measure changes in physical properties resulting from interaction with ionizing radiation. The most common types of pocket dosimeters include ionization chamber dosimeters and electronic personal dosimeters (EPDs) ^[8].

Ionization Chamber Pocket Dosimeter: This type of dosimeter uses an ionization chamber, where radiation interacts with air inside the chamber and ionizes the gas. The ionized particles produce an electrical charge that is then measured to determine the radiation dose. These dosimeters typically have a small analog scale or digital readout to provide an immediate measurement of the accumulated dose.

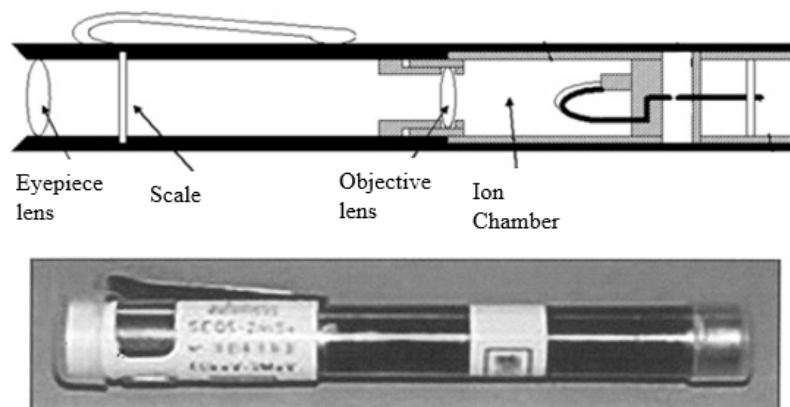


Fig: 10.3. Ionization chamber Pocket Dosimeter

Electronic Personal Dosimeter (EPD): EPDs are more advanced versions that utilize semiconductor or scintillation detectors and a digital display to provide real-time readings. These dosimeters can measure both accumulated radiation dose and instantaneous dose rates. Some EPDs offer additional features like alarm settings, which can alert the user when they exceed preset radiation thresholds, making them especially useful for high-risk environments ^[9].



Fig: 10.4. Electronic Personal Dosimeter

One of the main advantages of pocket dosimeters is their real-time feedback capability. This immediate response is invaluable for radiology professionals, allowing them to quickly assess their exposure and take necessary precautions if they are approaching unsafe radiation levels. Unlike passive dosimeters, which require analysis in a laboratory, pocket dosimeters provide instant data, making them ideal for situations where quick action is required. In addition to their real-time capabilities, pocket dosimeters are lightweight and easy to use, making them practical for daily monitoring in clinical settings. They are also durable, often designed to withstand the conditions of a busy radiology department. However, a limitation of pocket dosimeters, especially the ionization chamber type, is their limited range and the potential for drifting or needing recalibration over time. In high-radiation environments, more sensitive and specialized equipment may still be required for accurate monitoring.

Table: 10.5. Comprehensive Overview of Pocket Dosimeters

Category	Feature	Description
Types of Pocket Dosimeters	Ionization Chamber Pocket Dosimeter	Measures radiation exposure using an ionization chamber. It generates ion pairs when radiation passes through, providing a direct reading of exposure levels.
	Electronic Pocket Dosimeter (EPD)	Uses electronic sensors to measure radiation exposure. Provides real-time digital readings and may include alarms that activate when preset radiation thresholds are exceeded.
Advantages	Real-Time Monitoring	Provides immediate feedback on radiation exposure, helping individuals to take corrective actions promptly and avoid overexposure.
	Portability	Compact, lightweight design makes it easy to carry around for continuous radiation monitoring, ensuring that exposure levels can be tracked throughout the day.
	Ease of Use	Equipped with user-friendly digital displays or analog scales, allowing for easy interpretation of readings without needing specialized training.
	Immediate Feedback	Electronic pocket dosimeters give instant alerts when exposure reaches preset thresholds, providing a layer of safety by notifying users of excessive radiation.
Disadvantages	Limited Duration of Monitoring	Traditional ionization chamber dosimeters may require resetting or recalibration after a specific time period, limiting their ability to provide continuous monitoring.
	Battery Dependence (for EPDs)	EPDs rely on batteries for operation, and if the battery malfunctions or depletes, the dosimeter can become inactive, leading to gaps in monitoring.

	Potential for Overexposure	If not properly reset or calibrated, pocket dosimeters may provide inaccurate readings, which could result in an incorrect assessment of radiation exposure.
	Cost	While generally affordable, advanced electronic dosimeters can be more expensive than passive dosimetry methods, such as thermoluminescent dosimeters (TLDs).
Limitations	Limited Range	Pocket dosimeters, especially ionization chamber types, may have a restricted range for radiation dose measurement, making them unsuitable for high-radiation environments.
	Environmental Sensitivity	Older or analog pocket dosimeters may be sensitive to environmental factors such as temperature, humidity, and mechanical shock, which can affect their accuracy.
	No Permanent Record	Unlike TLD badges, pocket dosimeters generally do not provide a long-term, permanent record of exposure over time, limiting their ability to provide historical data.

Construction of Pocket dosimeter: The basic construction of a pocket dosimeter, particularly the direct-reading type commonly used in radiology and radiation-related fields, is designed to be compact, portable, and capable of giving immediate readings of accumulated radiation dose. These dosimeters are typically used for personal monitoring, allowing healthcare professionals and radiology staff to track their radiation exposure in real time. A typical pocket dosimeter consists of the following key components:

- 1. Ionization Chamber:** This is the core sensing element of the dosimeter. It is a small, gas-filled chamber (usually air or a special inert gas) where ionizing radiation enters and interacts with the gas molecules, causing ionization. The number of ions generated is proportional to the amount of radiation the dosimeter is exposed to.
- 2. Electrometer System:** Inside the chamber is a fine quartz fiber or metallic wire attached to an electrostatic scale or an electronic system. As radiation ionizes the gas, it causes a change in the electric charge on the fiber or wire, which moves in response. The amount of deflection indicates the amount of radiation absorbed, which can be read directly through a small built-in viewer or optical system.
- 3. Viewing Window or Eyepiece:** A small magnifying lens or window is included at one end of the dosimeter, allowing the user to look inside and view the fiber's position on a graduated scale. The scale is typically calibrated in units such as milliroentgens (mR) or microsieverts (μSv), representing the cumulative dose.
- 4. Charging Port and Charger:** Before use, a pocket dosimeter must be charged using a portable dosimeter charger. Charging resets the fiber to its zero position. As radiation is absorbed, the fiber gradually moves, allowing cumulative dose tracking throughout the work period.
- 5. Protective Outer Casing:** The dosimeter is enclosed in a sturdy, metal or plastic casing that shields the sensitive internal components from mechanical damage, dust, and moisture, while still allowing radiation to penetrate and be measured.

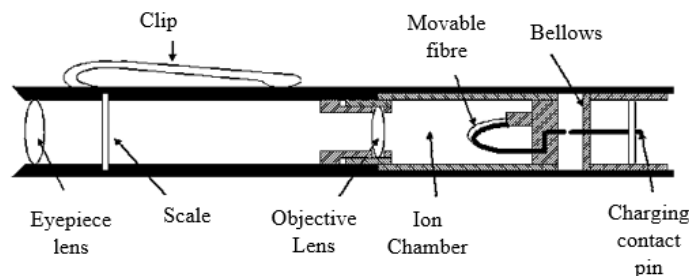


Fig: 10.5. Components of Pocket Dosimeter

Pocket dosimeters are especially useful in radiology for immediate feedback and for tracking short-term exposures, such as during fluoroscopy procedures or when working near portable X-ray machines. Though more modern digital dosimeters are now common, pocket dosimeters remain a reliable and quick tool for real-time dose estimation in many radiological settings.

Table: 10.6. Comparison between TLD Badge and Pocket Dosimeter

Feature	TLD Badge	Pocket Dosimeter
Principle of Operation	Measures accumulated radiation using thermos-luminescent materials that emit light when exposed to radiation.	Measures real-time radiation exposure, usually through ionization chambers or semiconductor detectors.
Type	Passive dosimeter	Active dosimeter
Real-Time Monitoring	No, it provides cumulative data after analysis.	Yes, real-time readings of radiation exposure.
Data Storage	Stores radiation dose until analyzed in a lab.	Provides continuous, real-time readings and may store data (in digital versions).
Readout Method	Requires laboratory analysis to read the dose, often using a light-sensitive reader.	Immediate digital or analog readout on the device's display.
Portability	Small and wearable, but requires periodic retrieval for analysis.	Extremely portable and can be worn throughout the day, offering constant monitoring.
Sensitivity	Highly sensitive, suitable for low-level radiation monitoring.	May vary; electronic versions can be highly sensitive, while ionization chamber types may not be as sensitive to low doses.
Cost	Generally more affordable, especially for passive dosimetry.	Can be more expensive, especially for advanced electronic models.
Calibration	Needs periodic calibration by professionals.	Needs occasional calibration, especially for electronic types.
Duration of Use	Can be used for long periods but requires reset or replacement after analysis.	Can be used continuously, though batteries may need to be replaced (for electronic versions).
Maintenance	Minimal, as it's a passive system, but must be handled carefully to avoid damage.	Regular maintenance required, especially for electronic versions (battery replacement, recalibration).
Suitability for High Radiation	Excellent for high levels of radiation exposure.	Suitable for low to moderate radiation levels; some models may struggle with high radiation doses.
Exposure Alerts	No alerts; requires lab analysis to determine exposure.	Often includes alarms that activate when preset radiation levels are exceeded.
Accuracy	Very accurate but depends on proper handling and analysis.	Accuracy depends on the model; digital EPDs can be very accurate.
Usage Frequency	Typically worn for weeks or months before analysis.	Can be used daily and continuously worn during shifts.
Compliance and Regulation	Widely accepted and often mandated in regulated environments.	Accepted but may not be as widely regulated or required in all industries.

10.2.3. Film Badge

A film badge radiation dosimeter is one of the earliest and most extensively utilized devices for monitoring individual exposure to ionizing radiation in occupational settings. It is particularly employed in environments such as medical imaging facilities, nuclear power plants, research laboratories, and industrial radiography, where personnel may be routinely exposed to radiation. The dosimeter functions by employing a photographic film as

the sensing element, which provides a permanent, cumulative record of the radiation dose received over a defined monitoring period, typically one month. The fundamental principle behind the film badge dosimeter is based on the photographic effect of ionizing radiation. When exposed to radiation such as X-rays, gamma rays, or beta particles, the silver halide crystals embedded in the photographic film undergo ionization. This interaction causes a latent chemical change that becomes visible only after photographic development. Upon processing in a controlled laboratory environment, the exposed regions of the film darken due to the reduction of silver ions to metallic silver. The optical density (degree of darkening) of the developed film is directly proportional to the amount of radiation absorbed, allowing for quantification of the radiation dose via comparison with calibrated standards^[10]. Once the monitoring period concludes, the badge is returned to a dosimetry laboratory for analysis. Technicians measure the film's optical density in specific regions and compare the results to calibration curves to determine the equivalent dose received by the wearer. Although film badge dosimeters are unable to provide real-time dose readings and are subject to environmental factors such as heat and humidity, they have been widely adopted due to their cost-effectiveness, simplicity, and ability to provide a cumulative exposure history. Despite being largely replaced in many settings by more advanced dosimetry technologies—such as thermoluminescent dosimeters (TLDs) and electronic personal dosimeters (EPDs)—film badges continue to represent a significant milestone in the development of radiation protection practices.

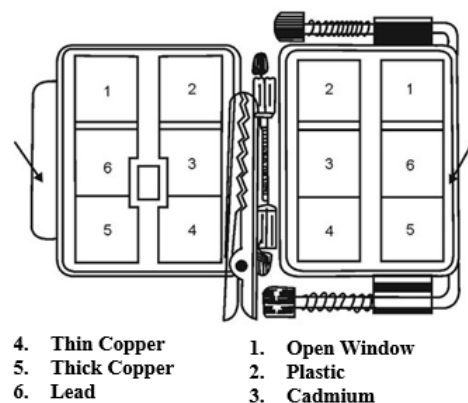


Fig: 10.6. Film Badge Dosimeter

Construction of film badge: The construction of a film badge radiation dosimeter is designed to be both simple and effective for monitoring cumulative exposure to ionizing radiation in occupational settings. At the heart of the dosimeter is a small piece of photographic film, usually a duplex film composed of two layers with different sensitivities, coated with silver halide crystals that react chemically when exposed to radiation such as X-rays, gamma rays, or beta particles. This film is enclosed in a light-tight wrapper, typically made of black paper or plastic, which protects the film from exposure to visible light while allowing ionizing radiation to pass through. The wrapped film is placed inside a durable plastic or metal badge holder, which provides mechanical protection and houses multiple radiation filters. These filters are made from different materials such as aluminum, copper, lead, plastic (PMMA), and sometimes tin or cadmium, each of which attenuates radiation to varying degrees depending on the type and energy of the incident radiation. Additionally, an open window section is included to allow unfiltered radiation to strike the film, making it sensitive to low-energy beta and X-rays that might otherwise be blocked by denser materials. The combination of these filters allows the film badge to distinguish between different types and energies of radiation by comparing the degree of darkening under each filtered area after development. The badge holder often includes identification markings such as the user's name or ID number, monitoring period, and institutional details. These features ensure proper tracking and documentation of individual exposure. After a typical monitoring period of about one month, the badge is returned to a dosimetry lab, where the film is processed and the optical density is measured to determine the radiation dose received. Overall, the construction of a film badge dosimeter is compact, reliable, and tailored for ease of use, making it a valuable tool

for radiation protection, despite being gradually replaced by more advanced digital dosimeters in many modern facilities. A film badge typically consists of the following components:

1. **Photographic Film:** At the core of the dosimeter is the photographic film, which acts as the radiation-sensitive element. The film is usually a duplex film (i.e., two layers of film with different sensitivities), composed of silver halide crystals (typically silver bromide or silver chloride) suspended in a gelatin matrix and coated onto a plastic base. When exposed to ionizing radiation, these crystals undergo ionization, creating a latent image that becomes visible upon development. It Records cumulative radiation dose based on film darkening (optical density) and also Provides a permanent and archivable record of exposure.
2. **Plastic or Metal Holder:** The film packet is placed inside a plastic or metal badge holder, typically made of durable, lightweight materials such as aluminum or polycarbonate. The holder ensures physical protection of the film and is designed to be easily clipped onto clothing, usually at chest level. It Supports and protects the internal components of the dosimeter. Often labeled with worker identification and monitoring period information.
3. **Light-Tight Film Wrapper:** The film is sealed within a light-proof packet made from black paper or plastic material. This wrapper prevents exposure to visible light, which could fog the film and interfere with accurate radiation dose readings. It protects the film from light while allowing penetration of ionizing radiation. Additional layers may include moisture-resistant coatings to protect against humidity.
4. **Filters:** The film badge dosimeter includes six distinct windows, each equipped with a specific material or filter designed to selectively attenuate different types and energies of ionizing radiation.
 - **The first window**, known as the open window, contains no shielding material and permits all types of radiation to pass through without attenuation. It is particularly sensitive to low-energy beta particles and soft X-rays, making it useful for detecting radiation that may not penetrate other filtered windows. This window also serves as a baseline reference for comparison with the filtered exposures in other regions of the badge.
 - **The second window** consists of a plastic filter made from low atomic number materials such as polycarbonate or Perspex (PMMA). This filter closely mimics the attenuation properties of human soft tissue, allowing beta particles to pass while attenuating low-energy photons. It is primarily used to assess beta radiation exposure and is often interpreted alongside data from the open window to distinguish between beta and photon radiation.
 - **The third window** incorporates a yellow-coloured cadmium filter, approximately 1 mm thick, and is specifically used to detect thermal neutron radiation. Cadmium has a high neutron absorption cross-section, making it effective for this purpose, especially in nuclear environments.
 - **The fourth window** features a thin copper filter, 0.15 mm thick and typically green in color, designed to attenuate low-energy X-rays. It provides information on the presence and energy range of diagnostic X-ray radiation, which is common in medical imaging environments.
 - **The fifth window** is constructed from thicker copper, approximately 1 mm thick, and is pink in color. This filter is used to detect higher-energy X-rays, offering greater attenuation than the thinner copper window and allowing for better discrimination of X-ray energy ranges.
 - **The sixth window** is composed of lead, with a thickness of 1 mm and a black color code. Due to its high atomic number and density, lead is highly effective in attenuating high-energy gamma radiation. This window is crucial for identifying and quantifying exposure to penetrating gamma rays, especially in radiology, nuclear medicine, and industrial radiography settings.

Table: 10.7. Advantages, Disadvantages, and Limitations of Film Badge

Category	Details
ADVANTAGES OF FILM BADGE	
Cost-Effective	Film badges are relatively inexpensive to produce, making them an affordable option for monitoring large groups of workers, especially for organizations with limited budgets.

Wide Availability	Film badges are widely used and available from various manufacturers, making them easy to source in many parts of the world.
Historical Data	Film badges provide a permanent record of exposure, which can be stored and analyzed for long periods, useful for historical documentation and tracking cumulative exposure.
Can Measure Low Levels of Radiation	Film badges are sensitive enough to detect low doses of radiation, making them useful for routine monitoring in environments with generally low but continuous radiation levels.
Versatile	Can measure various radiation types (alpha, beta, gamma) when appropriate filters are used, allowing use in different radiation environments.
DISADVANTAGES OF FILM BADGE	
Requires Laboratory Analysis	Film badges need to be processed in a laboratory to interpret the readings. This introduces a delay in obtaining results after the exposure period.
Not Real-Time Monitoring	Film badges do not provide real-time radiation dose information. Results are only available after the film has been developed and analyzed, which is a significant delay.
Sensitive to Light and Temperature	Film badges are sensitive to environmental factors like light and temperature. Exposure to light before development can cause false readings, and extreme temperatures can affect accuracy.
Limited Sensitivity	While they measure radiation exposure, film badges may not be as sensitive as newer dosimetry technologies like electronic dosimeters or TLDs, limiting their use in certain situations.
Physical Damage	The film can be damaged by mechanical forces or environmental conditions (e.g., humidity), leading to inaccurate readings. Handling must be done carefully.
LIMITATIONS OF FILM BADGE	
No Real-Time Feedback	Film badges do not provide immediate feedback on radiation dose, causing delays in taking actions to reduce exposure if necessary.
Bulkier than Modern Dosimeters	Film badges are relatively bulkier and less comfortable to wear compared to modern dosimetry options like electronic dosimeters, which are more compact and provide real-time readings.
Cannot Detect Very High Radiation Doses	Film badges are generally not suitable for high-radiation environments as they may not give accurate readings for very high doses.
Inconsistent Readings for Low Doses	Film badges may be less accurate in detecting very low doses, which could be problematic in environments where workers are exposed to low radiation levels over long periods.
Handling and Storage Requirements	Film badges require proper storage to avoid exposure to light, temperature fluctuations, and physical damage, necessitating careful handling and storage, which can be cumbersome.

11.2.4. OSLD (Optically Stimulated Luminescent Dosimeter)

OSLD is a modern radiation dosimeter that is used for measuring ionizing radiation exposure. It works on the principle of optically stimulated luminescence, where a special material, typically aluminum oxide (Al_2O_3), is used to trap electrons when exposed to ionizing radiation. These trapped electrons are released when the dosimeter is exposed to light, specifically a laser, which stimulates the material to emit light in proportion to the amount of radiation it has been exposed to. The intensity of the light emitted is then measured and used to calculate the radiation dose. One of the significant advantages of OSLDs is their sensitivity and precision. They can detect very low levels of radiation, making them highly suitable for monitoring workers in environments where radiation exposure is minimal but needs to be closely monitored over time. Unlike older dosimeters, such as film badges or TLDs, OSLDs provide immediate readings and can be read multiple times without degrading the material or affecting its performance. They are also resistant to environmental factors like humidity and temperature, which can often compromise other types of dosimeters.



Fig: 10.7. OSLD

However, OSLDs do have some disadvantages. They are typically more expensive than traditional dosimeters, which could be a barrier in settings where large numbers of dosimeters are required. Additionally, although OSLDs can provide excellent accuracy, they require specialized equipment to read the luminescent signal, which may not be available in all facilities. Despite these challenges, the OSLD has become a popular choice in radiation safety programs due to its durability, reliability, and ease of use for long-term radiation monitoring in various fields, including healthcare, nuclear power plants, and industrial applications.

Table: 10.8. Comparison between TLD, OSLD, Film Badge, and Pocket Dosimeter:

Feature	TLD (Thermoluminescent Dosimeter)	OSLD (Optically Stimulated Luminescence Dosimeter)	Film Badge	Pocket Dosimeter
Principle of Operation	Uses thermoluminescent crystals that emit light when heated after exposure to radiation.	Uses a luminescent material that releases light when stimulated by light after radiation exposure.	Uses a photographic film that darkens in response to radiation exposure.	Measures radiation exposure via ionization of gas or electronic sensors.
Measurement Method	Requires heating and analysis in a lab to measure emitted light.	Requires exposure to light to stimulate emission, then analyzed for intensity.	Requires film development in a lab to measure darkening.	Provides real-time or cumulative radiation measurements, with digital or analog output.
Real-Time Monitoring	No real-time monitoring; requires lab analysis.	No real-time monitoring; requires light stimulation and analysis.	No real-time monitoring; requires lab development.	Real-time monitoring (especially for electronic versions).
Sensitivity to Radiation	Sensitive to both low and high doses, with high accuracy.	Sensitive to low and high radiation doses, offering high precision.	Sensitive to a range of radiation types but less sensitive to very low doses.	Sensitivity varies by type, generally good for routine monitoring.
Types of Radiation Detected	Can detect alpha, beta, gamma, and X-rays.	Can detect alpha, beta, gamma, and X-rays.	Can detect alpha, beta, gamma, and X-rays with appropriate filters.	Can detect gamma, X-rays, and some types of beta radiation.
Portability	Compact and portable, often worn in a badge.	Portable, typically worn similarly to TLDs.	Compact but can be bulkier and less comfortable to wear.	Highly portable and worn on person, especially for electronic versions.

Cost	Moderate, with the need for periodic calibration and laboratory analysis.	Moderate, more expensive than TLDs due to technology but offers excellent accuracy.	Inexpensive to produce, especially for large groups or organizations.	Varies; traditional models are cheap, but electronic models are pricier.
Reusability	Reusable; requires periodic calibration and lab analysis.	Reusable; similar to TLDs but with different analysis methods.	Can be reused, but films need to be replaced periodically.	Generally reusable, but electronic versions may need battery replacements.
Calibration Requirement	Requires periodic calibration for accurate results.	Requires periodic calibration, often more sensitive to calibration.	Needs proper handling and occasional checks for accuracy.	Requires periodic calibration, especially electronic versions.
Ease of Use	Requires lab analysis; not user-friendly for immediate results.	Requires light stimulation and analysis; not suitable for immediate feedback.	Requires film development and analysis, making it slow for immediate feedback.	Very user-friendly, especially for real-time electronic dosimeters.
Durability	High durability but sensitive to physical damage.	High durability with minimal wear, but susceptible to light exposure.	Prone to damage from light, heat, and humidity.	High durability, especially for electronic versions.
Accuracy	High accuracy, especially for high radiation doses.	Offers high accuracy, particularly in low-dose environments.	Moderate accuracy; may not be as sensitive in low radiation environments.	Accuracy varies; electronic versions provide precise measurements, while ionization types are less sensitive.
Data Logging	No data logging; must be analyzed post-exposure.	No data logging; requires post-exposure analysis.	No data logging; data is stored in physical form on the film.	Electronic models can log data, providing a record of exposure over time.
Typical Applications	Used in medical and occupational radiation monitoring, including nuclear power plants, and research.	Used in medical, nuclear, and environmental monitoring, especially in precision radiation environments.	Widely used in occupational and medical radiation monitoring.	Used in medical, nuclear, and industrial settings, especially for real-time monitoring.
Limitations	Requires lab analysis, no real-time feedback, sensitive to handling and storage.	Requires light exposure for analysis, not suitable for real-time monitoring.	Sensitive to light and temperature, requires lab processing, no real-time feedback.	Limited range for traditional models, reliance on battery life, may not handle extreme exposures.

10.2.5. Radio-Photo-Luminescent (RPL) Dosimeter

Radio-photo-luminescence (RPL) dosimetry, which utilizes silver-activated phosphate glass, became a significant advancement in individual radiation monitoring during the 1990s. In this technique, exposure to ionizing radiation creates stable defect centers in the glass through a non-ionizing excitation process. When the glass is subsequently

exposed to ultraviolet (UV) light, it emits visible light, the intensity of which is directly proportional to the absorbed radiation dose. A key advantage of RPL over other methods like thermoluminescence (TL) and optically stimulated luminescence (OSL) is that the luminescent centers are not destroyed during the readout process. These centers remain extremely stable over time, exhibiting negligible fading even after several years, which allows for accurate, repeatable dose measurements—ideal for long-term monitoring ^{[11][12]}.



Fig: 10.8. RPL Dosimeter

Development of RPL technology began earlier, with major improvements in the 1960s led by Toshiba Corporation. Enhancements to the RPL glass composition and the refinement of reader designs significantly increased the sensitivity and reliability of RPL dosimeters, making them practical for routine health physics applications. One of Toshiba's early commercial models, the BD-2, featured two RPL glass dosimeters: a smaller one in the lower compartment designed for high-dose measurements, and a larger, more sensitive one in the upper section for detecting lower doses. To correct for the over-response of glass to low-energy gamma and X-rays, a tin filter was incorporated to flatten the energy response curve. These innovations laid the foundation for the widespread use of RPL dosimetry in radiation safety and monitoring programs.

❖ Personnel Monitoring Services (PMS) Providers for Radiation Facilities in India

All radiation workers are required to wear TLD (Thermoluminescent Dosimeter) badges issued by AERB-authorized laboratories to record occupational radiation exposure. These badges are available on a chargeable basis from the following laboratories:

Table: 10.9. PMS Provider for radiation safety in India

Sr. No.	Region / States Covered	Laboratory Name & Address	Contact Details
1	Southern Region: Andhra Pradesh, Telangana, Tamil Nadu, Karnataka, Kerala, Puducherry, Andaman & Nicobar, Lakshadweep	Avanttec Laboratories (P) Ltd. Plot No. 17, Arignar Anna Industrial Estate, Mettukuppam, Vanagaram, Chennai – 600095, Tamil Nadu	☎ Phone: 044 2386 2025 ☎ Fax: 044 2386 2024 ✉ Email: tldlab@avanttec.net 🌐 Website: www.avanttec.net
2	Western Region: Maharashtra, Gujarat, Rajasthan, Goa, Dadra & Nagar Haveli, Diu	Renentech Laboratories Pvt. Ltd. C-106, Synthofine Industrial Estate, Off Aarey Road, Goregaon East, Mumbai – 400063, Maharashtra	☎ Phone/Fax: 022 40037474 ✉ Email: rms@renentech.com 🌐 Website: www.renentech.com
3	Central, Northern & North Eastern Regions: (All other Indian states not covered above)	Ultra-Tech Laboratories Pvt. Ltd. Cloth Market, Kumhari (Bhilai–Raipur NH 6), P.O. Kumhari, Dist. Durg – 490042, Chhattisgarh	☎ Phone: +91 7821 247020 / +91 99812 12431 ✉ Email: utechlab@rediffmail.com 🌐 Website: www.ultratechlab.com

4	All Defence Institutions (Pan India)	Defence Laboratory, Jodhpur: (Details managed directly through Ministry of Defence and authorized radiation safety channels)	–
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10.3. AREA MONITORING

Area monitoring is a fundamental aspect of radiation protection that involves the systematic measurement and evaluation of radiation levels within a specific location or facility. It is primarily conducted in environments where radioactive materials are handled or where radiation-producing equipment is in operation. The primary objective of area monitoring is to ensure that radiation levels remain within permissible limits to protect workers, the public, and the environment from potential exposure to ionizing radiation. This type of monitoring is essential in nuclear power plants, medical institutions, research laboratories, industrial facilities, and environmental sites where radiation sources are present.

The key objectives of area monitoring include:

- Ensuring Workplace Safety – Area monitoring helps in detecting radiation leaks, spills, or unintentional exposure, thereby ensuring a safe working environment for employees handling radioactive materials.
- Compliance with Regulations – National and international regulatory bodies such as the International Atomic Energy Agency (IAEA), Environmental Protection Agency (EPA), and Occupational Safety and Health Administration (OSHA) mandate radiation monitoring in workplaces. Compliance with these guidelines is necessary to prevent legal and environmental consequences.
- Preventing Excessive Exposure – Continuous monitoring of radiation levels helps in identifying potential hotspots where radiation intensity may be higher than expected, allowing for immediate corrective actions.
- Early Detection of Radiation Incidents – Area monitoring systems provide real-time alerts in case of sudden increases in radiation levels, enabling prompt responses to prevent accidents.
- Environmental Protection – Monitoring radiation in surrounding areas helps in detecting and controlling radioactive contamination, ensuring that ecosystems and communities remain safe from long-term radiation exposure.

Methods of Area Monitoring: Area monitoring is conducted using a variety of techniques and instruments that detect and measure radiation. The methods used depend on the type of radiation being monitored, the level of sensitivity required, and the specific application. The most commonly used methods include:

1. Fixed Monitoring Stations – These are permanently installed radiation detectors placed in key locations within a facility to provide continuous radiation monitoring. They are often used in nuclear power plants and research laboratories.
2. Portable Radiation Survey Meters – Handheld devices, such as Geiger-Muller counters and scintillation detectors, are used for routine inspections and spot-checks in different areas of a facility. These are useful for identifying radiation hotspots and assessing contamination levels.
3. Airborne Radiation Monitoring – This method involves using air sampling devices to detect radioactive particles or gases present in the atmosphere. It is particularly useful in nuclear facilities and industrial sites where radioactive dust or fumes may be released.
4. Surface Contamination Monitoring – Wipe tests and contamination detectors are used to assess the presence of radioactive materials on surfaces such as floors, walls, equipment, and protective clothing.
5. Real-time Monitoring Systems – Advanced radiation monitoring systems equipped with remote sensors and automated alerts provide continuous data on radiation levels. These systems are integrated with software that allows for real-time tracking, data analysis, and reporting.

Table: 10.10. Types of Radiation Detected in Area Monitoring

Type of Radiation	Characteristics	Common Monitoring Applications
Alpha Radiation (α)	Heavy, highly ionizing particles; harmful if inhaled or ingested; low penetration (stopped by paper or skin)	Nuclear fuel processing, radioactive waste management
Beta Radiation (β)	High-energy electrons; moderate penetration (stopped by plastic or glass); can cause skin burns	Laboratories, industrial applications, beta-emitting isotope usage
Gamma Radiation (γ)	Highly penetrating electromagnetic waves; requires lead or concrete shielding	Nuclear power plants, medical imaging (X-rays, CT scans), radiation therapy
Neutron Radiation	Neutral particles associated with nuclear reactions; deeply penetrating; requires specialized neutron detectors	Nuclear reactors, research facilities, particle accelerators

❖ Challenges in Area Monitoring

Despite its effectiveness, area monitoring presents several challenges that must be addressed to ensure accurate and reliable radiation detection. One of the primary challenges is instrumentation sensitivity, as radiation detectors must be highly sensitive to detect even low levels of radiation while minimizing false alarms. Overly sensitive instruments may trigger unnecessary alerts, while less sensitive ones might fail to detect hazardous exposure. Another significant challenge is calibration and maintenance, as radiation monitoring devices require regular calibration to maintain accuracy. Without proper maintenance, detectors may provide incorrect readings, leading to either unnecessary panic or undetected exposure risks. Additionally, data interpretation poses a challenge, as large volumes of radiation data need to be analyzed systematically to identify trends, potential risks, and necessary preventive actions. Misinterpretation of data could result in delayed responses to radiation hazards. Finally, response time is a critical factor in radiation safety. In cases of radiation leaks or sudden increases in exposure levels, immediate action is required to protect personnel and the environment. Quick decision-making, effective evacuation plans, and timely communication are essential to mitigating risks and preventing radiation-related incidents. Addressing these challenges through technological advancements, regular training, and adherence to safety protocols is crucial for ensuring the effectiveness of area monitoring in radiation protection. Area monitoring devices are specialized instruments used to measure and assess radiation levels in specific locations where radioactive materials are handled or radiation-producing equipment is in operation. These devices play a crucial role in ensuring workplace safety, regulatory compliance, and environmental protection by continuously detecting and recording radiation exposure levels. They are used in various settings, including nuclear power plants, hospitals, laboratories, industrial facilities, and environmental monitoring sites.

10.3.1. Ionization Chamber and Related Gas-Filled Radiation Detectors

An ionization chamber is a fundamental type of gas-filled radiation detector used for measuring ionizing radiation. It consists of a sealed chamber containing a specific gas (such as air, argon, or a noble gas mixture) and two electrodes an anode and a cathode across which a high voltage is applied. When ionizing radiation enters the chamber, it interacts with the gas, resulting in the ionization of gas molecules, producing free electrons and positive ions. Due to the applied electric field, the electrons migrate toward the positive electrode (anode) and the positive ions move toward the negative electrode (cathode). This movement of charge carriers generates a measurable electric current, which is directly proportional to the intensity of the incident radiation. To ensure that recombination of ions does not occur before collection, a minimum threshold voltage typically ranging from tens to several hundred volts is maintained across the electrodes.

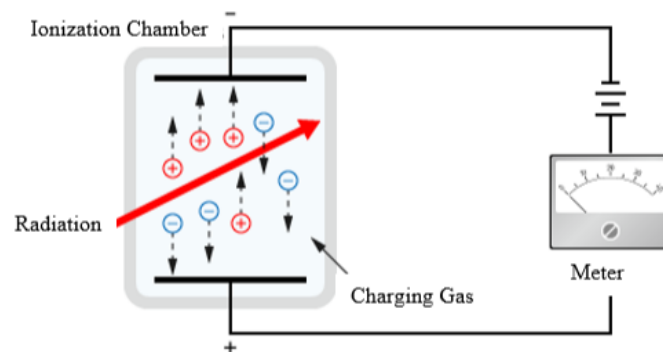


Fig: 10.9. Gas Filled Detector

The Geiger-Müller (G-M) tube is a type of gas-filled detector, operating at even higher voltages. In this case, the voltage is sufficient to cause a full avalanche multiplication of ionizations from a single interaction, producing a large, uniform output pulse. While the G-M counter is highly sensitive, it does not retain information about the energy of the radiation, unlike proportional counters. A proportional counter represents another type of the ionization chamber in which the applied voltage is increased beyond the standard ionization chamber operating range. In this mode, the initial electrons produced by the primary ionizing event gain enough kinetic energy from the electric field to cause secondary ionizations of the gas molecules. This process results in an amplified electrical signal, which remains proportional to the energy of the incident radiation, allowing for energy discrimination and spectroscopy applications.

A. Geiger-Müller (GM) Counter

The Geiger-Müller (GM) counter is one of the most popular and widely utilized radiation detectors due to its simplicity, portability, and effectiveness in detecting a range of ionizing radiation types. The core of the GM counter is the Geiger-Müller tube, which is a gas-filled tube equipped with electrodes at either end. When ionizing radiation, such as alpha particles, beta particles, or gamma rays, enters the tube, it interacts with the gas inside, causing ionization and creating electron-ion pairs. These charged particles are then attracted to the electrodes, where they produce an electrical pulse. This pulse is subsequently counted by the device's attached electronic circuitry, providing a readout of the radiation detected. The GM counter is particularly sensitive to beta radiation and gamma rays, and it is widely used to detect these forms of ionizing radiation. The type of gas used inside the tube and the overall design of the GM counter determine its sensitivity, with some counters being more adept at detecting specific types of radiation. For instance, a GM counter may be more sensitive to beta particles, while others may perform better with gamma radiation. However, despite its versatility and effectiveness for many common applications, the GM counter has some notable limitations.

Table: 10.11. Historical Evolution of the Geiger-Müller Counter and Its Applications

Year/Period	Milestone	Description
1908	Discovery of Ionization by Radiation	Hans Geiger, working with Ernest Rutherford, demonstrated that alpha particles could ionize air. This ionization could be detected and counted using an early electrical system, laying the groundwork for radiation detection technology.
1928	Invention of the Geiger Counter	Hans Geiger and Walther Müller developed the Geiger-Müller (G-M) tube, a sensitive detector capable of detecting alpha, beta, and gamma

		radiation. This innovation became the basis for the widely used Geiger-Müller Counter.
1930s– 1940s	Adoption in Scientific Research	The G-M counter became a vital tool in nuclear physics, aiding research into radioactive decay, cosmic rays, and particle physics. It played a central role in advancing early atomic science.
1940s– 1950s	Use in Nuclear Industry and Medical Field	With the advent of nuclear technology during WWII and beyond, G-M counters were extensively used for radiation monitoring in nuclear plants, research institutions, and medical facilities, ensuring safety and supporting radiological research.
1950s– 1970s	Standard Radiation Survey Instrument	G-M survey meters became standard instruments for radiation detection. Portable and battery-powered models were employed by radiation safety officers, medical physicists, and emergency responders across various sectors.
Modern Day	Continued Use with Digital Enhancements	Despite the emergence of advanced detectors, G-M counters remain widely used due to their simplicity, reliability, and affordability. Modern versions feature digital readouts, data logging, and connectivity, while still based on the original 1928 principle.

One significant drawback is that the GM counter does not provide detailed information about the energy of the detected radiation. Unlike more sophisticated detectors, such as scintillation counters or semiconductor detectors, the GM counter cannot differentiate between different energies of radiation, limiting its ability to offer precise spectral information. Another limitation is that the GM counter can become saturated when exposed to high radiation levels. This means that when the radiation intensity exceeds a certain threshold, the counter may not be able to register the full extent of the radiation, leading to inaccurate or incomplete readings. This makes the GM counter unsuitable for environments where very high radiation doses are expected or in situations requiring high precision. Additionally, the GM counter has a reduced ability to distinguish between different types of ionizing radiation. While it can detect alpha particles, beta particles, and gamma rays, it cannot differentiate between them based on their energy levels, which is a critical factor in some applications. Its efficiency also tends to decrease when measuring low-energy X-rays or gamma rays, which can further limit its usefulness in specific contexts. Despite these limitations, the Geiger-Müller counter remains a valuable tool in a variety of settings. One of its primary applications is in environmental radiation monitoring, where it is used to measure radiation levels in the environment and detect contamination from radioactive sources. It is also frequently employed in personal dosimetry to monitor radiation exposure in workers who may be at risk, such as those in medical facilities, nuclear power plants, or research laboratories. The portability and ease of use of the GM counter make it an excellent option for initial radiation surveys, as it provides quick, real-time readings that can help assess the immediate radiation environment. In laboratory settings, GM counters are commonly used to detect radioactive contamination on surfaces or equipment, allowing researchers and safety personnel to quickly identify areas that may require further decontamination. The simplicity of the GM counter, along with its ability to detect various types of ionizing radiation, makes it an indispensable tool for general radiation monitoring and safety. In summary, while the Geiger-Müller counter has its limitations, it continues to be an important and reliable device for detecting and measuring ionizing radiation in a wide range of applications.

A Geiger-Müller (GM) counter is a device used to detect and measure ionizing radiation, such as alpha, beta, and gamma rays. The GM counter is one of the most commonly used instruments for radiation detection due to its simplicity, portability, and effectiveness in measuring radiation in various environments. It consists of several key components that work together to detect ionizing particles and convert their interactions into measurable electrical signals. The central component of a GM counter is the Geiger-Müller tube itself, a cylindrical device that serves as the detection unit. This tube is filled with an inert gas (usually argon, neon, or helium) at low pressure and is positioned between two electrodes. The inner electrode is a thin wire, and the outer electrode is the metallic body of the tube. The tube is typically housed in a durable casing made from metal or plastic, which helps protect the internal components and ensures the device's robustness. The GM tube is sealed with a window at the end to allow radiation to enter, usually made of a thin mica or other transparent materials that are thin enough to permit

radiation penetration without significantly affecting the measured particles. When ionizing radiation, such as an alpha particle, beta particle, or gamma ray, enters the tube and interacts with the gas inside, it ionizes the gas molecules, creating positive ions and free electrons. The presence of these charged particles in the gas creates an electric current. The applied voltage between the inner wire and the outer metal casing of the tube creates an electric field within the gas. When the radiation causes ionization, the free electrons are accelerated toward the anode (the thin wire), while the positive ions are attracted to the cathode (the outer metal casing). This movement of ions and electrons leads to a current pulse

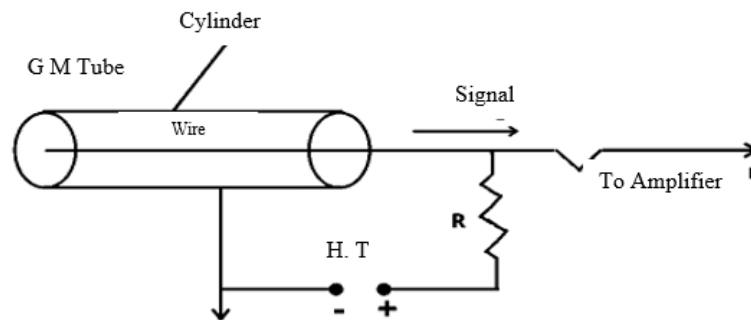


Fig: 10.10. Construction of GM Counter

The magnitude of the voltage across the tube is set such that when an ionizing event occurs, the resulting ionization will trigger a gas discharge. This discharge results in a short, sharp electrical pulse that is proportional to the ionization event, not the energy of the radiation itself. This pulse is collected by the electronics of the GM counter and converted into a count that represents an instance of radiation detection. In order to amplify the signal and avoid continuous discharge, a quenching gas (often added to the inert gas mixture) is used to stop the ionization process after each event. This ensures that the GM tube can reset and be ready to detect the next ionizing particle. Quenching gases help the tube return to its normal state by absorbing the excess energy, preventing a continuous discharge, and restoring the gas to its non-ionized state. The electronics of the GM counter are designed to process these pulses. The detected signals are typically amplified, counted, and then displayed on a digital or analog readout. The count rate displayed on the readout is a measure of the number of ionizing events (or radiation particles) detected per unit of time, typically displayed in counts per minute (CPM) or counts per second (CPS). The higher the radiation intensity, the more frequent the ionization events and, therefore, the higher the count rate. Additionally, the GM counter often includes a scaler or counter circuit to keep track of the total number of counts over a specified period of time, allowing for cumulative radiation measurements. Some GM counters also include audible alerts, which produce a clicking sound for every detected ionization event, providing a real-time, auditory indication of radiation presence. Key Components of GM Counter includes:

1. **Geiger-Müller Tube:** The heart of the GM counter, it contains the gas-filled chamber with electrodes that detect ionizing radiation. The tube is often equipped with a window, typically made of mica, which allows the radiation to enter.
2. **Electrodes:** The inner wire (anode) and the outer metal casing (cathode) form the electric field inside the GM tube. When ionization occurs, the resulting free electrons are attracted to the anode, and the positive ions are attracted to the cathode.
3. **Gas and Quenching Gas:** The GM tube is filled with an inert gas, and a small amount of quenching gas (such as halogen or organic vapour) is added to stop the discharge after each ionizing event. This allows the tube to reset and be ready for the next detection.
4. **High Voltage Power Supply:** The GM tube operates at a high voltage, typically between 300 and 900 volts, applied between the anode and cathode. The high voltage accelerates the electrons toward the anode, enabling the detection of the ionizing particles.
5. **Pulse Counter:** The pulses generated by each ionizing event are counted by an internal counter. The number of pulses per unit of time indicates the radiation intensity. The count rate is often displayed on a

meter or screen.

6. **Audio Indicator:** Many GM counters provide an audible signal, such as a clicking sound, for every detected radiation event, giving a real-time indication of the presence of radiation.

Applications of GM Counters: GM counters are used extensively in a wide variety of applications. In health and safety, they are employed to monitor radiation exposure in workplaces such as nuclear power plants, hospitals, and research labs. They are also used for environmental monitoring to detect radioactive contamination in air, water, and soil. Additionally, geological surveys often use GM counters to study naturally occurring radioactive materials in rocks and ores. In nuclear physics research, GM counters provide essential data on radiation sources and decay processes. In conclusion, the construction of a Geiger-Müller counter involves a combination of a gas-filled tube, high-voltage power supply, pulse counting mechanism, and various safety and amplification components. Together, these elements make the GM counter a reliable, widely used device for detecting ionizing radiation, essential in fields ranging from radiation safety to scientific research.

B. Proportional Counters

A proportional counter is similar to a Geiger-Müller counter but operates at a lower voltage and in a different mode. In a proportional counter, the amount of ionization produced in the gas is directly proportional to the energy deposited by the incident radiation. This results in an output signal whose amplitude reflects the energy of the radiation. Proportional counters are highly useful for energy discrimination and can measure the energy of alpha, beta, and gamma radiation.

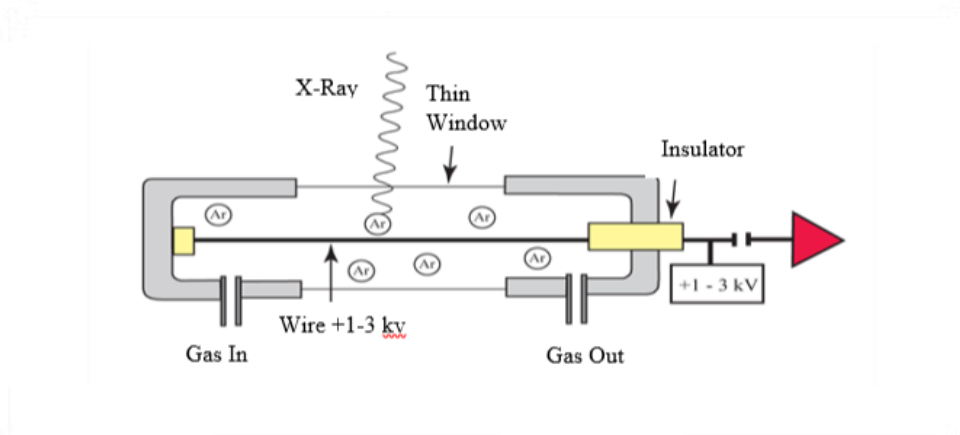


Fig: 10.11 Proportional Counter

The main advantage of proportional counters over GM counters is their ability to provide information about the energy of the detected radiation, which allows for better identification and analysis of the type of radiation involved. However, proportional counters tend to be more complex and expensive compared to GM counters. These detectors are commonly used in spectroscopy and research applications, where precise energy measurements and the ability to distinguish between different types of radiation are essential. Proportional counters are also used in radiation protection, especially in environments where mixed radiation fields are present.

C. Scintillation Detectors

Scintillation detectors are another widely used technology for detecting ionizing radiation. These detectors work by using a scintillating material that emits flashes of light (or "scintillations") when it interacts with ionizing radiation. The flashes of light are then detected by a photomultiplier tube (PMT), which converts the light into an electrical signal that can be measured. One of the major advantages of scintillation detectors is their ability to discriminate between different types of radiation based on the energy of the scintillation produced.

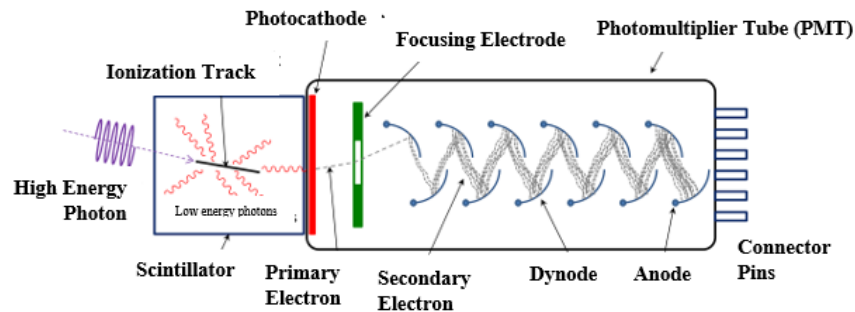


Fig: 10.12. Scintillation Detector

Additionally, scintillation detectors are capable of measuring the energy of the radiation, making them highly effective for applications where both detection and energy analysis are needed. Scintillation detectors are widely used in nuclear medicine, radiation therapy, environmental monitoring, and material testing. In medical imaging, scintillation detectors are used in positron emission tomography (PET) and gamma cameras for detecting gamma radiation emitted from radioactive tracers. In environmental monitoring, scintillation detectors are used to measure radiation levels in the environment and monitor potential contamination from nuclear power plants.

D. Semiconductor Detectors

Semiconductor detectors are advanced radiation detectors that offer high resolution and precision in detecting ionizing radiation. These detectors are based on semiconductor materials, such as silicon (Si) or germanium (Ge), which produce electron-hole pairs when ionizing radiation interacts with the material. The movement of these charge carriers in response to the radiation creates a measurable electrical signal, which can be analyzed to determine the energy and intensity of the radiation. The high resolution of semiconductor detectors makes them ideal for applications requiring precise energy measurements, such as spectrometry and dosimetry. Semiconductor detectors are particularly effective at detecting gamma rays, X-rays, and some types of beta radiation. The main advantages of semiconductor detectors are their high energy resolution, excellent sensitivity, and ability to measure low levels of radiation accurately. However, they tend to be more expensive and require careful calibration and temperature control to maintain optimal performance.

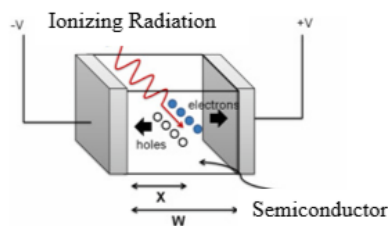


Fig: 10.13. Semiconductor Detector

Principle of Semiconductor Detectors: At the heart of semiconductor detectors is the semiconductor material, which behaves as both an insulator and a conductor depending on its energy state. When ionizing radiation (such as gamma rays, X-rays, or alpha particles) interacts with the semiconductor material, it causes the generation of electron-hole pairs. These free charge carriers (electrons and holes) are then separated by an applied electric field, resulting in an electrical signal that can be measured. The magnitude of the signal is proportional to the energy deposited by the radiation, allowing for high-resolution energy measurements. There are several types of

semiconductor detectors, each with distinct advantages and specific applications. These detectors are used in a wide variety of fields, including medical imaging, nuclear power monitoring, environmental radiation assessments, and scientific research. Germanium detectors, in particular, are often used for gamma-ray spectrometry because of their excellent energy resolution. These detectors are commonly used in research and nuclear physics, as well as in high-precision medical imaging and radiation safety applications.

Table: 10.12. Types of Semiconductor Detectors

Type of Semiconductor Detector	Operation	Applications
Silicon Detectors (Si Detectors)	Silicon detectors typically use p-n junctions or diodes. When ionizing radiation interacts with the silicon, it generates electron-hole pairs, which are separated by an electric field, producing a measurable current proportional to the energy deposited by radiation.	<p>Particle Detection: Used in high-energy physics experiments (e.g., at CERN) to track and measure the energy of charged particles like electrons and protons.</p> <p>Medical Imaging: Employed in PET scanners and X-ray systems for their high resolution and energy discrimination.</p> <p>Radiation Monitoring: Utilized in personal dosimeters to monitor radiation exposure in environments like hospitals and nuclear facilities.</p>
High-Purity Germanium (HPGe) Detectors	HPGe detectors operate similarly to silicon detectors but with germanium, offering superior energy resolution. These detectors are cooled to liquid nitrogen temperatures (around 77K) to reduce thermal noise and enhance performance.	<p>Gamma Spectroscopy: Used extensively in nuclear physics, environmental monitoring, and radiological assessments to identify specific isotopes based on their gamma-ray emission spectra.</p> <p>Nuclear Medicine: Used to image and quantify the distribution of radiopharmaceuticals in the body.</p> <p>Environmental Radiation Monitoring: Detects environmental radiation near nuclear plants or radioactive waste sites, helping to identify and quantify specific isotopes.</p>
Silicon Drift Detectors (SDDs)	SDDs feature a unique drift region that allows charge carriers to move efficiently toward a small anode, providing high count rates and good energy resolution at room temperature. No cryogenic cooling is required.	<p>X-ray Fluorescence (XRF): Used in XRF spectrometry for material analysis, especially in non-destructive testing and surface analysis.</p> <p>Portable Radiation Detectors: Ideal for portable gamma-ray and X-ray spectroscopy systems due to their compact size and room temperature operation.</p> <p>Environmental Monitoring: Increasingly used in handheld devices for monitoring radiation in contaminated areas or for security purposes.</p>
Cadmium Telluride (CdTe) Detectors	CdTe detectors operate at room temperature by generating electron-hole pairs when radiation interacts with the material. They provide a balance between energy resolution, cost, and operational temperature.	<p>X-ray Imaging: Common in X-ray imaging systems and mammography, offering efficient detection at room temperature.</p> <p>Nuclear and Industrial Radiography: Used in industrial radiography and nuclear monitoring for detecting gamma radiation.</p> <p>Environmental Monitoring: Employed in environmental radiation monitoring for detecting gamma rays and X-rays in contaminated environments.</p>
Mercury Iodide (HgI ₂) Detectors	HgI ₂ detectors use mercury iodide crystals to generate electron-hole pairs when exposed to radiation. These	<p>High-Energy Gamma Ray Detection: Well-suited for detecting high-energy gamma rays and X-rays, ideal for nuclear spectroscopy.</p>

	carriers are collected to produce an electrical signal.	<p>Medical Imaging: Used in some medical X-ray imaging systems that require high resolution for specific diagnostic purposes.</p> <p>Military and Security Applications: Applied in military and homeland security contexts for detecting nuclear threats, due to their broad range of detection and high energy resolution.</p>
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Applications of Semiconductor Detectors: Semiconductor detectors are used in a variety of critical fields due to their precision and ability to provide detailed energy measurements. Key applications include:

- **Medical Imaging:** In positron emission tomography (PET), X-ray imaging, and mammography, semiconductor detectors offer high resolution and sensitivity, providing detailed images and ensuring accurate diagnostics.
- **Nuclear Spectroscopy:** In gamma-ray spectroscopy, nuclear physics, and environmental radiation monitoring, semiconductor detectors allow for precise identification and quantification of radioactive isotopes, making them invaluable in both research and regulatory contexts.
- **Environmental and Security Monitoring:** Due to their sensitivity and ability to detect low levels of radiation, semiconductor detectors are widely used in environmental radiation monitoring, security applications, and border control for detecting illicit radioactive materials.
- **Industry and Research:** Semiconductor detectors are used in industrial radiography, material testing, and non-destructive evaluation of products and structures. They are also used in high-energy physics experiments, such as particle detection at particle accelerators.

E. Neutron Detectors

Neutron detectors are specialized devices designed to detect neutron radiation, which differs from other types of ionizing radiation because neutrons are uncharged particles. Neutron detectors work by capturing neutrons and producing secondary reactions that can be detected and measured. There are several types of neutron detectors, including neutron scintillation detectors, neutron proportional counters, and semiconductor-based neutron detectors. One of the most common methods for neutron detection is the use of boron trifluoride (BF₃) detectors, which use the reaction between neutrons and boron to produce charged particles that can be detected. Other neutron detectors rely on reactions between neutrons and hydrogen (such as in liquid scintillation detectors), or neutron capture reactions in materials like helium-3. Neutron detectors are widely used in nuclear reactors, research laboratories, and industrial applications where neutron radiation is present. They are also essential in homeland security applications for detecting illicit nuclear materials.

End of Chapter

REFERENCE

1. Knoll, G. F. (2010). *Radiation Detection and Measurement* (4th ed.). Wiley.
2. Martin, J. E. (2013). *Physics for Radiation Protection: A Handbook* (3rd ed.). Wiley.
3. IAEA (International Atomic Energy Agency). (2017). *Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards* (No. GSR Part 3).
4. NCRP Report No. 57 (1984). *Instrumentation and Monitoring Methods for Radiation Protection*.
5. Turner, J. E. (2007). *Atoms, Radiation, and Radiation Protection* (3rd ed.). Wiley-VCH.
6. AERB (Atomic Energy Regulatory Board, India). *Regulatory Requirements for Operation of Radiation Facilities*.
7. Tsoufanidis, N., & Landsberger, S. (2015). *Measurement and Detection of Radiation* (4th ed.). CRC Press.
8. Kase, K. R., Bjarngard, B. E., & Attix, F. H. (1985). *The Dosimetry of Ionizing Radiation, Volume I*. Academic Press.
9. Beck, H. L., et al. (1980). *Health Physics Manual of Good Practices for Radiation Protection Monitoring*. U.S. Department of Energy.
10. US NRC (U.S. Nuclear Regulatory Commission). *Radiation Monitoring Instrumentation Regulatory Guide (Reg. Guide 8.13)*.
11. Becker K. Recent progress in radiophotoluminescence dosimetry. *Health Phys* 14: 17-32: 1968.
12. Yokota R, Nakajima S. Recent improvements in radiophotoluminescent dosimetry. In: Attix FH, ed. *Luminescence dosimetry. Proc Int Conf Lumin Dos June 21-23, 1965: 284-299; 1967.*