# Principles of Radiation Detection

## Ionization Methods for Measurement of Radiation

The interaction between radiation and matter is accompanied by a number of effects such as the emission of photons, charged particles and liberation of heat. All these effects can be used to detect radiation, measure particle flux density or intensity and the radiation spectra. The operation of many measuring devices is based on the ability of radiation to ionize molecules.

Different types of detectors can be characterized by the nature of the interaction of radiation with matter. Gas filled detectors operate by utilizing the ionization produced by radiation as it passes through a gas. Such a counter consists of two electrodes to which a certain electrical potential is applied. The space between the electrodes is filled with a gas. Ionizing radiation, passing through the space between the electrodes dissipates part or all of its energy by generating electron-ion pairs. They are charge carriers that move under the influence of the electric field. This induces a current on the electrodes, which may be measured through appropriate electronics. The charge produced by the radiation may be transformed into a pulse, in which case particles are counted individually.

A nucleonic pulse originates as transient voltage change across the output end of a radiation detector, as a result of charge deposited in the detector by the passage of ionizing radiation. Radiation detector generating a charge pulse can be represented by a circuit diagram shown in the Fig. 1

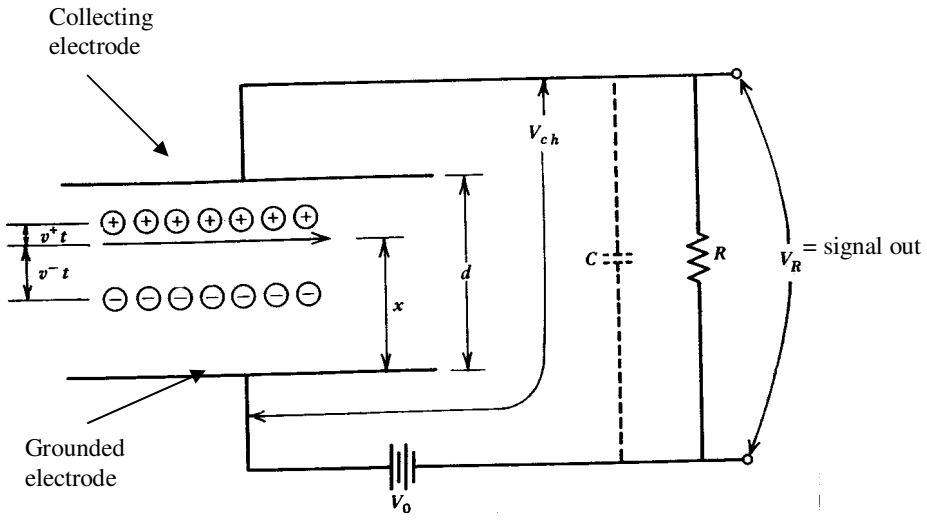



Figure 1 : The electronic circuit of parallel-plate ionization chamber

A voltage V is applied through a load resistance R, to a detector with a capacitance C, so that, in the absence of an ionizing event, the voltage across the detector is equal to V. Then a charge q is collected at one end of the electrodes, the voltage across them falls by an amount v, given by

$$V = \frac{q}{C}$$

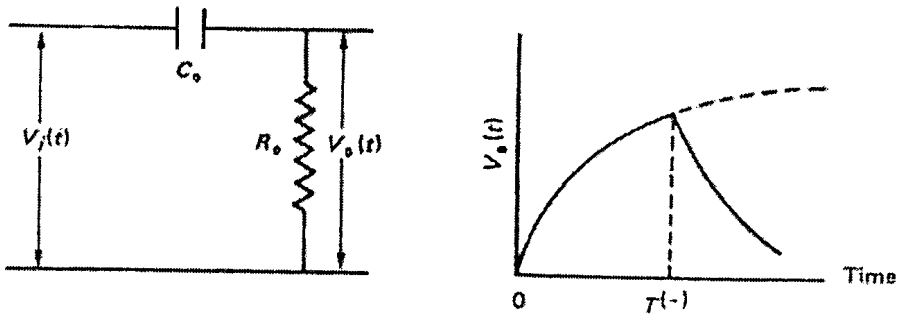



Figure 2 : Signal output from the RC circuit & its decay

Following this event the voltage recovers exponentially to its original value and the net effect is that a small, negative voltage pulse is superimposed on the much larger, positive dc potential. Normally, it is desirable to isolate the signal pulse from the much larger dc potential in order to avoid overloading of subsequent units. This is achieved by reading the signal out through a coupling capacitance, $C_e$, which transmits only ac voltages. The signal pulse then has the form illustrated in Fig. 2. It increases linearly because of the uniform rate of charge collection, to maximum value v, which is the pulse height. The pulse then decays exponentially with a decay time constant equal to $R_iC_i$.

## Relationship between High Voltage and charge collected.

A radioactive source of constant intensity is placed at a fixed distance from a gas counter. The high voltage (HV) applied to the counter may be varied with the help of a potentiometer. An appropriate meter measures the charge collected per unit time. If the HV applied to the counter is steadily increased, the charge collected per unit time changes as shown in Fig. 3.

***Region I*** : When the voltage is very low, the electric field in the counter is not strong, electrons and ions move with relatively slow speeds, and their recombination rate is considerable. As V increases, the field becomes stronger, the carriers move faster, and their recombination rate decreases up to the point where it becomes zero. Then the entire charge created by the ionizing radiation is being collected. That gives the saturation current known as Ionization region current.

***Region II*** : The recombination rate is zero and no new charge is produced. This is indicated as Ion saturation in Fig. 3.

***Region III*** : The electric field is so strong, in a certain fraction of the counter volume, that the electrons from the primary ionization acquire enough energy between collisions to produce additional ionizations. The gas multiplication factor: $K_s$ i.e., the ratio of the total ionization produced divided by the primary ionization is, for a given voltage, is independent of the primary ionization. The output of the counter is proportional to the primary ionization. The pulse height of the output is proportional to the energy dissipated inside the counter. Therefore, particle identification and energy measurement are possible. At the end of this proportional region, K may acquire a value of $10^3$ to $10^4$.

***Region IV*** : Beyond the proportional region, the electric field inside the counter is so strong that a single electron-ion pair generated in the chamber is enough to initiate an avalanche of electron-ion pairs. This avalanche will produce a strong signal with shape and height independent of the primary ionization and the type of particle, a signal that depends only on the electronics of the counter. This region is called the Geiger-Muller region.

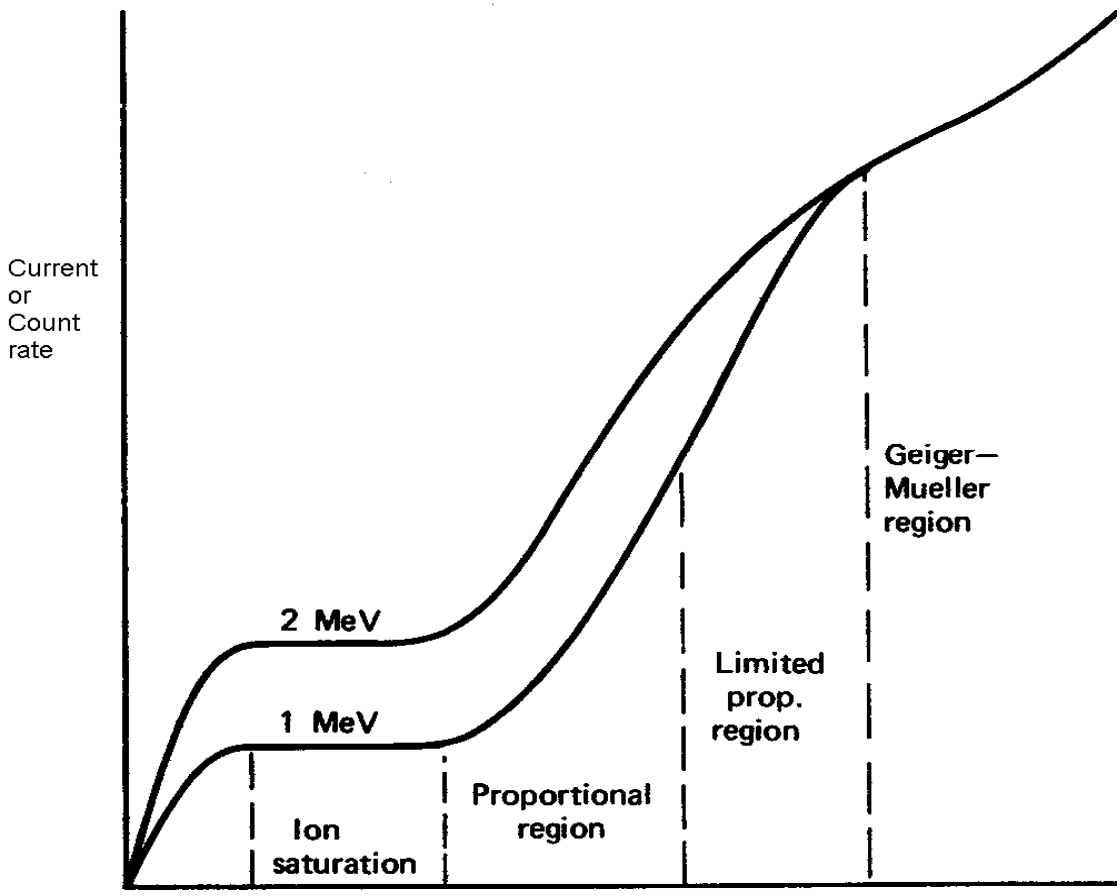



Figure 3. Characteristics of a general gas filled detector

**Different types of gas filled counters** :

Gas counters take their name from the voltage region in which they operate.

***Ionization Chambers*** : Operate in the ionization region. No charge multiplication takes place. Output signal is proportional to the particle energy dissipated in the detector. Since the signal is not large, only strongly ionizing particles such as alphas, protons, fission fragments and other heavy ions are detected.

***Proportional Counters*** : Operate in region III. Charge multiplication takes place. Output signal is still proportional to the energy deposited in the counters. Measurement of particle energy is possible. Identification of the type of particle is possible.

***G.M. Counters*** : Operate in region IV. It can be used for any kind of radiation. The signal is independent of the particle energy and its type. Provides information only about the number of particles. It has relatively long dead time (200 to 300 μs). Gas counters may be constructed in any of the three basic geometries: Parallel plate, cylindrical, Spherical.

For parallel plate, the electric field is given by

$$E = \frac{V_o}{d}$$

In the cylindrical chamber, the electric field is

$$E_r = \frac{V_o}{ln\left(\frac{b}{a}\right)} \times \frac{1}{r}$$

where

a = radius of the central wire

b = radius of the counter

r = distance from the center of counter.

d = distance between the parallel plates.

$V_o$ = Voltage applied

Strong electric fields can be maintained inside a cylindrical counter close to the central wire. For this reason, proportional and GM counters are manufactured with cylindrical geometry.A counter filled with a gas at a certain pressure may operate in any of the regions discussed depending on the combination of following parameters.

- Size of the counter,
- Size of the anode wire,
- Gas type, Gas pressure,
- Level of voltage.

Normally, gas counters are manufactured to operate in one region only.

# Geiger-Muller Counting system

### General Principles :

A radiation counting system is composed of a radiation detector for detecting the radiation and a recorder for recording the electrical pulses produced in the detector. A widely used radiation detector is a Geiger Muller detector tube. Cross sectional view of a typical GM tube is shown in Fig. 4. A GM tube consists of a very fine central anode and a shell, which serves as the cathode. The region surrounding the anode is filled with a gas, usually argon or neon, specially selected for the ease with which it can be ionized. A high electrical field is maintained between the electrodes. The sensitive volume is the portion surrounding the anode responding to the specific radiation. An energetic charged particle traversing through the sensitive volume will have high probability of producing one or more ion pairs (electron and positive ion). The electron is accelerated towards the anode and in a short distance, gains sufficient kinetic energy to produce a second ion pair in a chance encounter with a gas atom. These two electrons will now produce additional ion pairs and thus an avalanche is developed in which an enormous number of electrons of the order of $10^{10}$ are eventually collected by the

anode. This charge which will be collected in about 0.25 μs, appears across the capacitance of the tube plus the associated circuitry to produce a voltage pulse of amplitude ranging from 0.25 to 10 volts with a duration of about 100 μs. These values depend upon the design of the tube, its operating voltage and the characteristics of the external circuit. When the voltage across the tube is such that it is operating in the GM region, all pulses are of equal size irrespective of the number of ion pairs formed in the initial ionizing event.

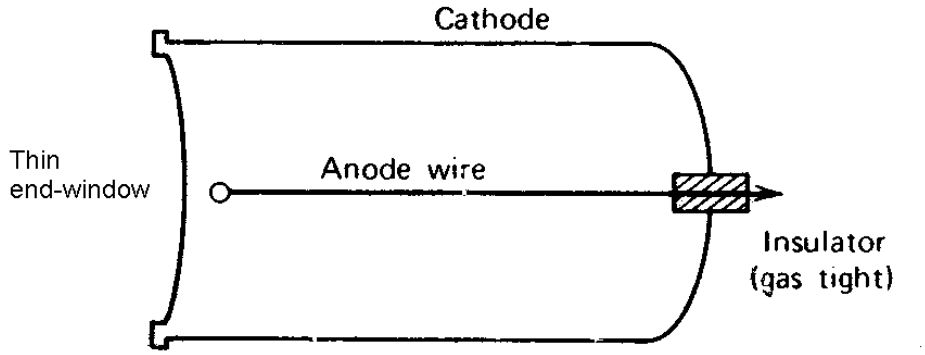



Figure 4: Cross sectional view of a typical Geiger Muller Detector

**Operating Characteristic of a GM Tube** :

When the tube is exposed to a constant radiation intensity and the voltage applied on the tube is slowly increased, a voltage will be reached at which GM tube begins to produce pulses as indicated by the recorder. This is the starting potential. As the voltage is increased, very rapid increase in counting rate is observed. This voltage is known as the threshold. Beyond the threshold further increase in the voltage over certain range will produce little effect on the counting rate. This region is known as the plateau. It should have a slope of less than 10% per 100 volts for good tubes. Within the plateau region, the proper operating voltage is selected. The operating voltage should be selected relatively close to the threshold voltage (within the lower 25% of the plateau) to preserve the life of the tube. Also the operating voltage should be selected at a point where the plateau shows minimum slope. If the voltage is increased beyond the plateau region, the counting rate begins to increase rapidly and the region of continuous discharge is reached. The shape of the high voltage (HV) plateau is as shown in the Fig. 5 and explained as follows.

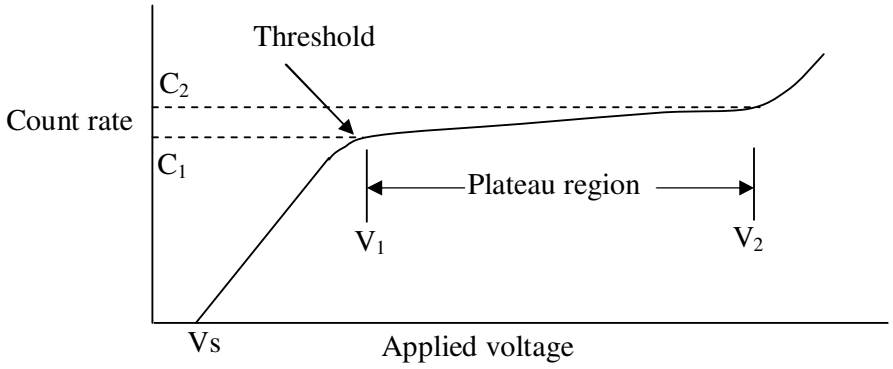



Figure 5: Countrate v/s applied voltage for GM detector

For very low voltage ($V<V_a$ ) the counting rate is zero. The scaler does not receive any signal because all the pulses are below the discriminator level. The counting rate keeps increasing with high voltage (HV), since more and more pulses are produced with a height above the discriminator level. This continues up to the point when $V = V_b$. For $V > V_b$, all the pulses are now above the discriminator level. Since all the pulses are counted, each pulse being recorded as one regardless of its height, the counting rate does not change. This continues up to $V = V_c$. Beyond that point, the counting rate will start increasing again because the HV is so high that spurious & double pulses may be generated. Counter should not be operated beyond $V = V_c$

**Quenching of the discharge** :

When the electrons are accelerated in the strong field surrounding the wire they produce, in addition to a new avalanche of electrons, considerable excitation of the atoms and molecules of the gas. These excited atoms and molecules produce photons when they de-excite. The photons in turn, produce photoelectrons in other parts of the counter. Thus the avalanche, which was originally located close to the wire, spreads quickly in most of the counter volume. During all this time, the electrons are continuously collected by the anode wire, while the much slower moving positive ions are still in the counter and form a positive sheath around the anode. When the electrons have been collected, this positive sheath, acting as an electrostatic screen, reduces the field to such an extent that the discharge should stop. However, this is not the case because the positive ions eject electrons when they finally strike the cathode, and since by that time the field has been restored to its original value, a new avalanche starts and the process just described is repeated. Clearly some means are needed by which the discharges is permanently stopped or quenched. Without quenching, a GM tube would undergo repetitive discharging. There are two general methods of quenching the discharge.

External Quenching : In external quenching, the operating voltage of the counter is decreased, after the start of the discharge until the ions reach the cathode, to a value for which the gas multiplication factor is negligible. The decrease is achieved by a properly chosen RC circuit as shown in Fig. 6. The resistance R (10 ohms or more) is so high that the voltage drop across it due to the current generated by the discharge ($i_d$) reduces the voltage of the counter below the threshold needed for the discharge to start ($V_o - i_d R$). The time constant (RC) is much longer than the time needed for the collection of the ions. As a result the counter is inoperative for an unacceptably long period of time. In other words, its dead time is too long.

Internal Quenching: The internal quenching method is accompanied by adding to the main gas of the counter a small amount of a polyatomic organic gas or a halogen gas. These have relatively large molecules, which tend to absorb the fluorescent emissions of the noble-gas atoms. They also have smaller excitation potentials than the latter, so their de-excitation photons have insufficient energy to ionize the gas and propagate the discharge further. For satisfactory photon quenching, the absorption spectrum of the quenching agent should match the emission spectrum of the noble gas. Methane and ethanol both satisfy these requirements.

Quenching agents with lower ionization potentials than the noble gas atoms tend to lose electrons in collisions with these ions, becoming positive ions themselves. Being heavier than the original ions, they approach the cathode more slowly, drawing electrons out by field emission. These cancel the ion and dissociate the molecule, dispersing energy without recycling the tube.

GM counters using an organic gas as quenching agent have a finite lifetime because of the dissociation of the organic molecules. Usually the GM counters last for $10^8$ to $10^9$ counts. The lifetime of a GM detector increases considerably if a halogen gas is used as the quenching agent. The halogen molecules also dissociate during the quenching process but there is a

certain degree of degeneration of the molecules which greatly extends the useful lifetime of the counter.

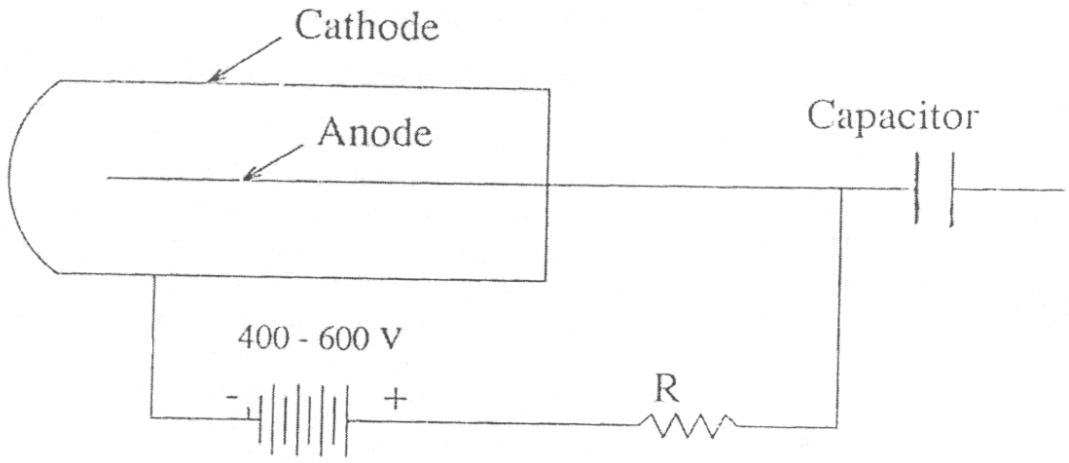



Figure 6: Circuitry for external quenching}

**Sensitivity of a GM tube** :

GM tubes are not equally sensitive to $\alpha$, $\beta$, and $\gamma$ radiations. Once the radiation reaches the sensitive volume of the counter, the efficiency of detection is 100% for $\alpha$, nearly 100% for $\beta$ and only 1 or 2% for $\gamma$ radiation. There is always a finite probability of a very high energy $\beta$ particle passing through the sensitive volume of the counter without undergoing any interaction with the gas atoms in the tube. Therefore, the efficiency of detection is less than 100% in such cases. Low efficiency of detection for $\gamma$ radiation is due to high penetrating power and high probability of $\gamma$ photon passing through the sensitive volume without interaction with the atoms of the gas or the wall material.

**Dead Time and Recovery Time of GM Tubes** :

It is found on close observation of oscilloscope that a small vertical pulse can sometimes be seen closely following one of the normal height for a particular applied voltage. These pulses occur when one ionizing event follows another at an interval too short for the counter to have completely recovered, a situation due to the fact that the positive ion sheath has not reached the cathode when the second ionizing event occurs. The longer the interval between the ionizing events the larger the second pulse will be, until it reaches its maximum. The time interval between the first full pulse and the delectability of another full pulse depends on the characteristics of the counter tube and is known as resolving time. This time interval is made up of two parts. The first part is the dead time and is the time after a count during which no pulse can be registered at all, even if an ionizing event occurs, because the electric field has collapsed and has not yet been reestablished. The second part is the recovery time, a time of increasing sensitivity, during which an ionizing event will give a pulse of amplitude less than that which is characteristic of the particular tube at the applied voltage. During this time the electric field is growing to its maximum value. At the end of the recovery time a full pulse is recorded. This is illustrated in Fig. 7.

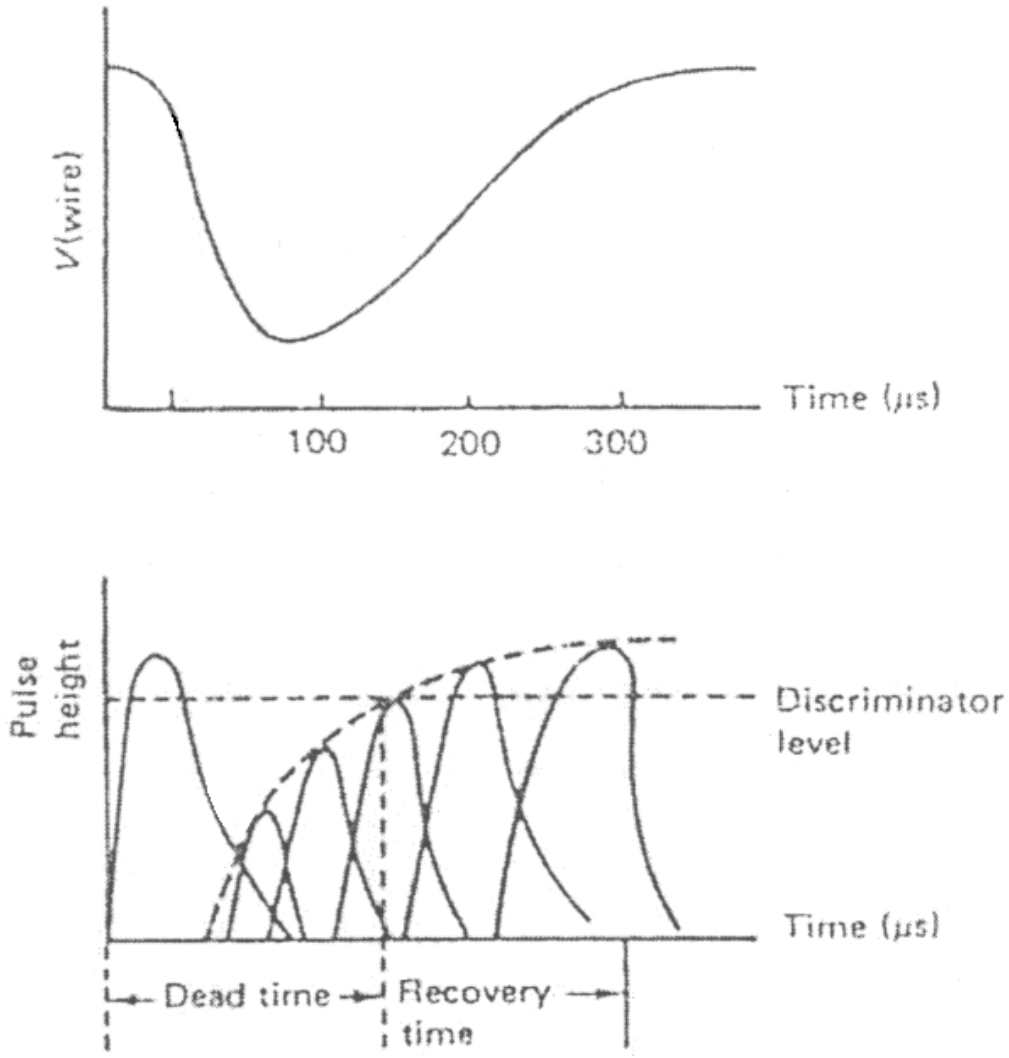



Figure 7: Dead time and recovery time for a GM detector

Consider two radioactive sources of strength $S_1$ and $S_2$. Let $n_1$, $n_2$ be the respective count rates recorded and $n_{12}$ be the count rate recorded when sources are taken together. Let $\tau$ be the resolving time. Let $N_1$, $N_2$ and $N_{12}$ be the corrected count rates respectively. Then we have

$$N_1 = \frac{n_1}{1 - n_1 \tau};\ N_2 = \frac{n_2}{1 - n_2 \tau};\ N_{12} = \frac{n_{12}}{1 - n_{12} \tau}$$

we have

$$N_1 + N_2 = N_{12}$$

substituting value of $N_1$, $N_2$ and $N_{12}$ in above equation.

$$\frac{n_1}{1 - n_1 \tau} + \frac{n_2}{1 - n_2 \tau} = \frac{n_{12}}{1 - n_{12} \tau}$$

solving the above equation and neglecting the higher powers of τ we get

$$\tau = \frac{n_1 + n_2 - n_{12}}{2 n_1 n_2}$$

# Scintillation Detectors :

Scintillators are materials- solids, liquids, gases- that produce sparks or scintillations of light when ionizing radiation passes through them. The amount of light produced in the scintillator is very small. It must be amplified before it can be recorded as a pulse or in any other way. The amplification or multiplication of the scintillator's light is achieved with a device known as photo multiplier tube. Amplifications of the order of $10^6$ are common for many commercial photo multiplier tubes. Apart from the photo-tube, a detection system that uses a scintillator is no different from any other. (Fig. 8)

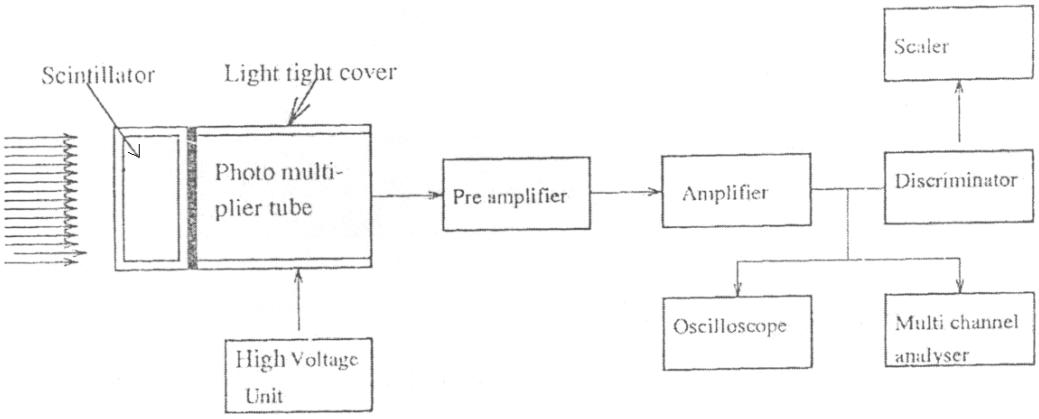



Figure 8 :Schematic of scintillation detector assembly

The operation of a scintillation counter may be divided into two broad steps.

- Absorption of incident radiation energy by the scintillator and production of photons in the visible part of electromagnetic spectrum.
- Amplification of the light by the photo multiplier tube and production of the output pulse.

### The mechanism of the scintillation process :

The luminescence of scintillator can be understood in terms of the allowed and forbidden energy bands of a crystal. In a crystal, the allowed energy states widen into bands as shown in Fig. 9. In the ground state of the crystal, the uppermost allowed band that contains electrons is completely filled. This is called the valence band. The next allowed band is empty (in the ground state) and is called the conduction band. An electron may obtain enough energy from the incident radiation to move from the valence to the conduction band. Once there, the electron is free to move anywhere in the lattice. The removed electron leaves behind a hole in the valence band, which can also move. Sometimes, the energy given to the electron is not sufficient to raise it to the conduction band. Instead, the electron remains electrostatically bound to the hole in the valence band. The electron-hole pair thus formed is called an excitation. In terms of energy states, the excitation corresponds to elevation of the electron to

a state higher than the valence but lower than the conduction band. The width of the excitation band is of the order of 1 eV, while the gap between valence and conduction bands is of the order of 8 eV.

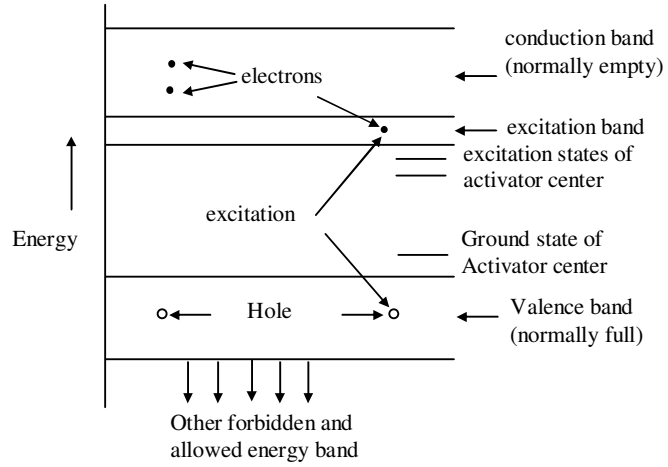


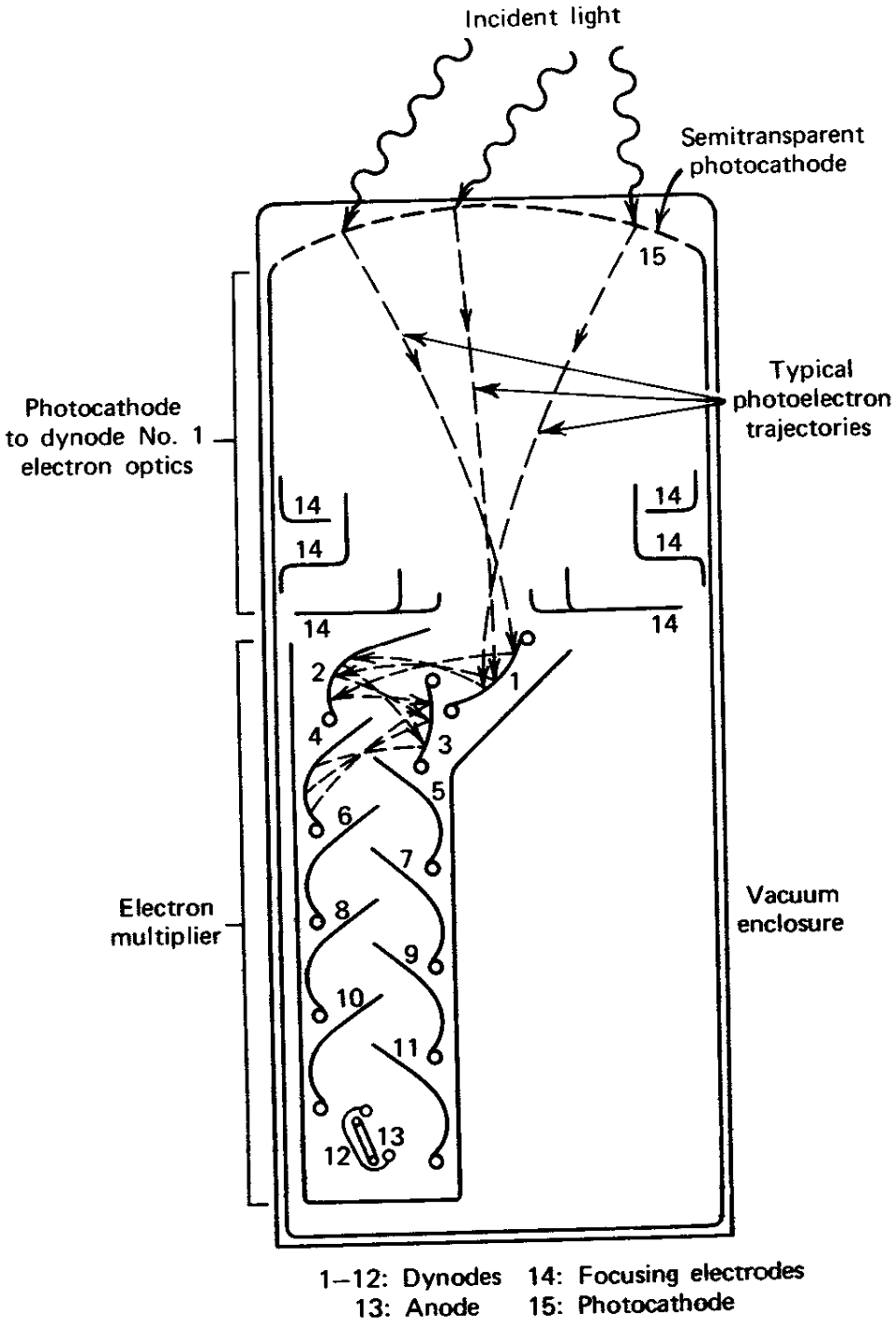

Figure 9: Allowed and forbidden energy band of a scintillation crystal

In addition to the excitation band, energy states may be created between valence and conduction bands because of crystal imperfections or impurities. Particularly important are the states created by the activator atoms such as thallium. The activator atom may exist in the ground state or in one of its excited states. Elevation to an excited state may be the result of a photon absorption or of the capture of an excitation or the successive capture of an electron and a hole. The transition of the impurity atom from the excited to the ground state, if allowed, results in the emission of a photon in times of the order of $10^{-8}$ s. If this photon has a wavelength in the visible part of the electromagnetic spectrum, it contributes to a scintillation. Thus, production of scintillation is the result of the occurrence of these events.

1. Ionizing radiation passes through the crystal,
2. Electrons are raised to the conduction band.
3. Holes are created in the valence band
4. Excitations are formed.
5. Activation centers are raised to the excited states by absorbing electrons, holes and excitations.
6. De-excitation is followed by the emission of a photon.

In a counting system using a scintillator, the light produced by the crystal is amplified by a photo multiplier tube and is transformed into an electric current. This current is fed into a RC circuit and a voltage pulse is produced.

The photo multiplier tube or the photo tube is an integral part of a scintillation counter. A photo multiplier consists of an evacuated glass tube with a photo cathode at its entrance and several dynodes in the interior as given in Fig. 9.




(PC - Photocathode, Fe - Focusing electrode, $D_1$...$D_9$ - dynodes)

Figure 9: Construction principle and circuit arrangement of a scintillation counter

The photons produced in the scintillator enter the photo tube and hit the photo cathode, which is made of a material that emits electrons when light strikes it. The electrons emitted by the photo cathode, are guided, with the help of an electric field, towards the first dynode, which is coated with a substance that emits secondary electrons, if electrons impinge upon it. The

secondary electrons from the first dynode move towards the second, from these towards the third, and so on. Typical commercial photo tubes may have up to 15 dynodes. The voltage difference between two successive dynodes is of the order of 80-120 V.

The photo cathode material used in most commercial photo tubes is a compound of cesium and antimony(Cs-Sb). The material used to coat the dynodes is either Cs-Sb or Ag-Mg.

**Dead time of scintillation counter*:***

The dead time or resolving time is the minimum time that can elapse after the arrival of two successive particles and still result in two separate pulses. For a scintillation counter, this time is equal to the sum of three time intervals.

- Time it takes to produce the scintillation, essentially equal to the decay time of the scintillator(0.23 msec).
- Time it takes for electron multiplication in the photo tube, of the order of 20-40 ns.
- Time it takes to amplify the signal and record it by a scalar. The recovery time of commercial scales is of the order of 1 μs. The time taken for amplification and discrimination is negligible.

By adding the three above components, the resulting dead time of a scintillation counter is of the order of 1-5 μs. This is much shorter than the dead time of gas-filled counter, which is of the order of tens of hundreds of micro seconds.

# Nuclear Sources and Detection:

Neutrons are produced in nuclear reactors and in spontaneous fission of nuclei.

***α,n* Reaction** :

Some sources in which neutrons are produced in the (α,n) reaction are the (Ra-Be), (Am-Be), (Po-Be) and (Pu-Be) sources. The $Po^{210}$, $Ra^{226}$ or $Pu^{239}$, α - emitting atoms are mixed uniformly with beryllium atoms and the mixture is enclosed in airtight metal capsule. The induced reaction is $Be^{9}(\alpha,n)Be^{8}$ $C^{12}$. The source intensity is stable for a Pu-Be neutron source since the half-life of Pu 239 is $2.4 \times 10^{4}$ years, and is $1.4 \times 10^{6}$ neutrons/s Ci.

**Photo Neutron Sources** :

Many radioactive substances emit γ quanta whose energies exceed the neutron binding energy in $Be^{9}$ nuclei (1.665 MeV) and D nuclei (2.225 MeV). The fact is exploited to obtain neutrons in the D (γ, n) H and $Be^{9}$ (γ, n) reactions. In a photo neutron source the capsule with the radioactive source ($Na^{24}$,$Ga^{72}$ etc.) is embedded in the target (Be- $D_2$ O).

**Spontaneous fission of nuclei** :

The nuclei $Cf^{252}{}_{98}$ can be used to obtain fission neutrons. The nuclei decays along two channels, spontaneous fission ($T_{1/2}$ = 86 Years) occurs in 3% of the nuclei. The useful lifetime of a californium source is determined by its α decay ($T_{1/2}$ = 2.6~years) into curium nuclei which accounts for 97% of the decay of the $Cf^{252}$ nuclei.

$$Cf\ {}^{232}_{98} \Rightarrow \left[ x\ {}^{A_1}_{Z_1} + y\ {}^{A_2}_{Z_2} + (3-4)n \right] + \left[ \alpha + Cm\ {}^{248}_{96} \right]$$

**Nuclear Reactor** :

Another powerful source of neutrons is the nuclear reactor. The neutrons are produced as a result of fission. The neutrons are guided out of the reactor into the laboratory through special

tubes. The spectrum of neutrons from a reactor is continuous. They are detected indirectly upon producing a charge particle or a photon, which is then recorded with the help of an appropriate detector. Nuclear reactions of the type (n, charged particle) are used for neutron detection. Endothermic reactions are used for fast neutron, and exothermic ones for thermal neutron.

**The BF counter** :

This is a proportional counter filled with $BF^3$ gas. The $BF^3$ counter detects the alpha and the lithium particles produced by the reaction

$$^{10}_{5}B + ^{1}_{0}n \rightarrow ^{4}_{2}He + ^{7}_{3}Li + 2.78\,MeV$$

Specification of commercial counters are:

Pressure of BF : From a little less than 1 to about 2 atm.

Operating voltage: Voltage range from 1000 to 3000V. It shows an almost flat plateau extending over 1000V or more.

Temperature: Maximum operating temperature is about 100 $^{O}$ C.

**Boron-lined counters**:

They are gas filled proportional counters in which the $^{10}B$ is coated on the walls of the counter. The sensitivity increases with the thickness of the $^{10}B$ coating. This has the flexibility of using a gas more appropriate than $BF_3$ .Hence the operating voltage is less and the counter is less sensitive to gamma rays. They may be used to detect neutrons in intense gamma fields.

*$^{3}He$ counters* :

Neutron detection by He is based on the reaction

$$^{3}_{2}He + ^{1}_{0}n \rightarrow ^{3}_{1}H \ + 765\,keV$$

Proportional counter filled with $^{3}$He are widely used for energy 0.0001 to 0.04 eV.

Efficiency of the counter can be increased by increasing the pressure.

The pressure is usually kept between (4 - 10 atm.).

Operating voltage is 3000- 5000V.

**Fission chambers**:

They are gas counters that detect the fragments produced by fission. Fission chambers operate in the Ionization region. The interior surface of the detector is coated with a fissile isotope. When fission takes place one of the fission fragments is emitted towards the center of the counter and is detected. The counting rate of a fission counter is proportional to the fission rate, which in turn is proportional to the neutron flux. $U^{235}$ fission cross section for thermal neutrons is about 500 times higher than that of fast neutrons. If the counter is coated with $U^{238}$ or $Th^{232}$, only fast neutrons with kinetic greater than 1 MeV are detected because the fission cross sections of these isotopes have thresholds at about that energy. They can be used for differentiation of thermal and fast neutron flux by using combination of $U^{235}$ and $U^{238}$ coated counters. The sensitivity of a fission counter decreases with exposure because of the depletion of the fissile isotope. If the counter wall is coated with a mixture of fertile and fissile materials like $U^{234}$ and $U^{235}$, then $U^{235}$ is partially replenished with new atoms produced by neutron capture in $U^{234}$.

Fission counters are used extensively for both out-of-core and in-core measurements of neutron flux in nuclear reactors. In out-of-core situations, they monitor the neutron population during the early stages of power accession when the neutron flux is very low. For in-core measurements, they are used for flux mapping [and consequently determination of the core power distribution]. Typical commercial fission counters for in-core use have diameters of about 1.5 mm, use enriched $U^{235}$ as the sensitive material and can be used to measure neutron fluxes up to $10^{18}$ neutrons/$cm^2$ - sec. Detection of fast neutrons by threshold activation reaction is based on the existence of an energy threshold for certain reactions of neutrons with nuclei. Thus, if one activates a foil made of such nuclei, the activity of the foil will give a measure of the neutron flux above the threshold.

- The foils have a small volume and low cross section. Therefore they do not disturb the neutron field.
- The foils are almost insensitive to gamma.
- Their small size makes the location of foils possible in places where no other spectrometer would fit.
- The counting equipment does not have to be carried to the radiation area.

**Semiconductor Detectors** :

They are solid state devices that operate essentially like ionization chambers. Solids are divided according to their electrical conductivity into three groups: insulators, conductors and semiconductors. In conductors, electrons can move freely at any voltage different than zero. In insulators, electrons cannot move under any voltage (except, when the voltage is so high that an electrical discharge occurs). In semiconductors, electrons cannot move at low temperatures (close to absolute zero) under any voltage. As the temperature of a semiconductor increases, however, electrons can move and electric current will flow at moderate voltages. In a free atom the electrons are allowed to exist only in certain discrete energy states. In solids, the energy states widen into energy bands.

In insulators, the highest allowed band, called the valence band, and is completely occupied. The next allowed band, called the conduction band is completely empty. No electric field or temperature rise can provide enough energy for electrons to cross the gap and reach the conduction band. In conductors, the conduction band is partially occupied. An electron close to the top of the filled part of this band will be able to move to the empty part under the influence of any electric field other than zero. In semiconductors, the valence band is full and the conduction band is empty, but the energy gap between these two bands is very small. At very low temperatures, close to T=0, the conductivity of the semiconductors is zero and the energy band looks like that of an insulator. As temperature increases, some electrons have enough energy to be able to move to the conduction band and conductivity appears. Actually, pure semiconductors are not available. All materials contain some impurities and for this reason they are impure or extrinsic, in contrast to a pure semiconductor, which is called intrinsic. In most cases, controlled amounts of impurities are introduced purposely by a process called doping, which increases the conductivity of the materials by orders of magnitude. Impurity atoms can create both n- type and p- type semiconductors. Electrons are the major carriers for n- type and holes are the major carriers for p- type semiconductors.

In ionization counters, the charge produced by the incident radiation are collected with the help of an electric field from an external voltage. In semiconductor detectors, the electric field is established by a process more complicated than in gas counters, a process that depends on the properties of n- and p- type semiconductors.

The performance of a semiconductor detector depends on the region of p-n junction where the electric field exists. Electrons and holes produced in that region find themselves in an environment similar to what electrons and ions see in a plate ionization chamber.

In a gas counter, the electrons mobility is thousands of times bigger than that of the ions. In semiconductors, the electron mobility is only about two to three times bigger than that of the holes. The time it takes to collect all the charge produced in a gas counter is of the order of milliseconds. In semiconductors, the sensitive region of the counter is only a few millimeters and the speed of electrons and holes is such that the charge carriers can traverse the sensitive region and be collected in times of the order of $10^{-7}$ s.

The advantages are

1. Superior in energy resolution.
2. Linear response over a wide range of energies.
3. Higher efficiency for a given size.
4. Fast pulse rise time.
5. Ability to operate in vacuum.
6. Insensitivity to magnetic fields.

# APPLICATION OF RADIOISOTOPES

**Density Gauges** : $\alpha$, $\beta$ and $\gamma$ transmission gauges can be used to measure changes in density of material, if the dimension of the tube or cylinder through which it passes remains the same. For example, a $\beta$ transmission gauge has been used to control and standardize packing of tobacco in cigarettes. Two ion chambers are located close together to minimize the effects of changes in ambient conditions. A $\gamma$ transmission gauge is often used to determine the density of a fluid in a pipeline. In the petroleum industry also, density gauges have been used for measurement of density of fluids and slurries in closed systems, so as to mark the easy diversion of liquids into different tanks.

**Neutron Gauge** : Neutron gauges play a major role in the mineral industry because of their different types of interactions.

Neutron - Neutron logging : The fast neutrons collide with atomic nucleus in the surrounding media and are slowed down. Hydrogen, in whatever chemical state it may be, is the most effective moderator. Chlorine has a very high capture cross-section for thermal neutrons, which is mainly due to chlorine-37. This helps in determining the moisture content of oil, to locate the position of the oil-water interface. The thermal neutrons are detected by BF proportional counter.

Neutron $\gamma$ logging : In this the $\gamma$ rays from the neutron capture in the surrounding media are detected. Chlorine present in water in the form of sodium chloride emits high energy $\gamma$ on neutron capture by chlorine-37. Thus, this principle can be used to locate the oil-water interface.

Tracer technique : The tracer method is a technique for obtaining information about a system or some part of a system by observing the behavior of a specific substance, the tracer, that has been added to the system.

Flow rate measurement with radioisotopes : Radioactive tracers have been used to measure flow velocities, volumetric measurement or turbulent flow in pipes and open channels and

rivers of known and unknown cross-sections. Measurements for large flow rates for oil in pipelines have been carried out.

**Detection of leaks in pipes** : Radioisotopes can be used to locate leaks in many pipe systems and are particularly useful when the pipes are buried since otherwise extensive excavation is necessary.

A small volume of radioactive solution is pumped into the main flow liquid. As the radioactive solution passes a leak some of it passes out into the soil. A battery operated detector and wire recorder in a hydraulically propelled sealed container follows the radioactive solution. A point source of radioisotopes is placed on the pipe at known distances. At the end of the test section, the recorder is played back to a recording rate meter whose paper recorder shows the position of radioactive leaks relative to distance markers.

**Determination of mixing efficiency** : There are many cases in industry where special additives must be thoroughly mixed with many times their weight of bulk material. If the additive can be made radioactive the check of uniformity of radioactivity of samples mean uniformity of mixing of the labeled additive. For the success the following points are to be considered carefully.

1. The additive itself and no other material should be radioactive.
2. Physical and chemical characterization of the additive must not be changed by irradiation, which makes it radioactive.
3. The isotope used should be emitting $\gamma$ rays of sufficient energy to penetrate from all parts of sample to the detector.
4. Amount of material being sampled must be same for each measurement.
5. The half-life should be small so that it would decay to a negligible level of activity by the time the product reached the consumer.

# HEALTH PHYSICS INSTRUMENTS

Health physics is the discipline that consists of all the activities related to the protection of individuals and the general public from potentially harmful effects of ionizing radiation. Health physics instruments are detectors having some unique requirements because their purpose is not to measure radiation but the effects of radiation on human tissue. Personnel monitoring is the evaluation of radiation doses received by the personnel working with radiation.

Film badge consists of a personnel monitoring film kept in a cassette containing a set of filters. A wide range of doses from 10 mrem to 1000 mrem of different types of radiation can be evaluated. The film serves as a permanent record. It can be used to access the radiation dose received from exposure to beta rays, X-rays, gamma rays or thermal neutrons. Special film is used for fast neutron monitoring. Film records track of recoil protons formed due to interaction of fast neutrons with hydrogen atoms in the film.

The TLD badge consists of a plastic cassette containing three TLD discs mechanically positioned over circular holes on a plated aluminium card. The three discs are so positioned that discs come under different filters (copper + aluminium, perspex and open ) respectively. These discs are the radiation recording devices, which are sensitive to X-rays, gamma and beta radiation. These can cover a wide range of doses from 10 mrem to 10,000 mrem. The X, gamma and beta radiation components of dose are estimated on the basis of differential filtration of the three discs.

Pocket dosimeter is a small ionization chamber, which is charged from time to time. The chamber potential decreases as the charge produced by ionizing radiation discharges the chamber. The momentary chamber potential is measured directly by a built-in electroscope. There are pocket dosimeters covering different ranges such as 0-200 mR, 0-5 R, etc.

Beta-gamma exposure rate meter is an ionization chamber type survey meter. This has 400 cc ionization chamber and can measure X and gamma radiation exposure rate, from 5 mR/h to 5 R/h in three ranges. The chamber is provided with a window and by opening the window beta radiations can also be monitored. This is useful for general purpose area monitoring and for checking the radiation levels around radiation source container.

Radiation survey meter is a GM counter type survey meter. It has a long glass walled GM counter and can cover X and gamma exposure rate from 0.1 mR/h to 20~mR/h in three ranges. It can also respond to high-energy beta radiations. It is very useful for low level area monitoring. This instrument, however, has a drawback that it does not respond at high radiation levels.

The third type of survey meter, wide range survey meter consists of a miniature GM counter, thus making it useful in high radiation levels. It can cover wide range of exposure rates, from 1 mR/h to 100 R/h in 5 ranges. This instrument is well suited in radiation emergencies and can be used for area monitoring and for monitoring leakage radiation around source containers. The detector can also be coupled through a telescopic extension rod for measurement of higher exposure rates, so that the exposure to the operator is considerably reduced during monitoring.

Non portable instruments are continuous monitors (e.g. air monitors) or personnel monitors (e.g. hand and foot monitor)

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