Radiation Detection Principles and Instruments

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Description

This document provides an outline and notes for providing a lecture on the principles of radiation detection and the instruments used in radiation detection.

Supporting Material



NET 130: Radiological Protection

Module 5: Radiation Detection Principles and Instruments

Overview

- Many instruments have been developed to detect radiation
- Based on knowledge of how radiation interacts with matter
 - Excitation
 - Ionization
 - Charged particles cause ionization directly through Coulombic interactions
 - EM radiation produces ion pairs in matter
 - Photoelectric effect
 - Compton scattering
 - Pair production
 - Neutrons produce ions through secondary mechanisms
- Four methods for detecting ionizing radiation:
 - lons collected to produce signal
 - Amplification of ionization to produce stronger signal
 - Fluorescence of a substance that has absorbed energy from radiation
 - Radiation-induced chemical reactions
- Three major types of detection instruments:
 - Nuclear instrumentation
 - Portable survey instruments and area monitors
 - Personnel monitoring devices

Gas-Filled Detectors

- · Detect incident radiation by measurement of two ionization processes
 - Primary process: ions produced directly by radiation effects
 - Secondary process: additional ions produced from or by effects of primary ions
 - Townsend Avalanche
- Primary and secondary ions produced within the gas are separated by Coulombic effects and collected by charged electrodes in the detector
 - Anode (positively charged electrode)
 - Collects the negative ions
 - Cathode (negatively charged electrode)
 - · Collects the positive ions

Gas-Filled Detector: Components

- Cylindrical gas chamber
 - Air
 - P-10 gas mixture (10% methane, 90% argon)
 - Helium
 - Neon
- Anode (+): Wire at center of chamber
- Cathode (-): Chamber walls
- Operating Principles
 - Voltage applied across electrodes
 - Incident radiation (α , β , or γ) enters chamber and ionizes the fill-gas
 - lons (+/-) separate and migrate to respective electrodes
 - Current output is generated and scaled to radiation level

- Voltage too low
 - lons may recombine and neutralize each other prior to reaching electrodes
- Proper operating voltage
 - All primary ion pairs are collected
- Voltage too high
 - Chamber becomes flooded with ions due to secondary ionizations caused by high-energy primary ions
 - Output current is no longer proportional to number of primary ionizations
 - Radiation events no longer measured
 - · Ionization "avalanche" propagated by input voltage itself
- Recombination Region
 - Applied voltage too low
 - Recombination occurs
 - Low electric field strength
- Ionization Chamber Region
 - (aka Saturation Region)
 - Voltage high enough to prevent recombination
 - All primary ion pairs collected on electrodes
 - Voltage low enough to prevent secondary ionizations
 - Voltage in this range called saturation voltage
 - As voltage increases while incident radiation level remains constant, output current remains constant (saturation current)
- Proportional Region
 - Gas amplification (or multiplication) occurs
 - Increased voltage increases primary ion energy levels
 - Secondary ionizations occur
 - · Add to total collected charge on electrodes
 - Increased output current is related to # of primary ionizations via the proportionality constant
 - (aka gas multiplication factor)
 - Function of detector geometry, fill-gas properties, and radiation properties
- Limited Proportional Region
- Collected charge becomes independent of # of primary ionizations
- Secondary ionization progresses to photoionization (photoelectric effect)
- Proportionality constant no longer accurate
- Not very useful range for radiation detection
- Geiger-Mueller (GM) Region
 - Any radiation event strong enough to produce primary ions results in complete ionization of gas
 - After an initial ionizing event, detector is left insensitive for a period of time (dead time)
 - Freed primary negative ions (mostly electrons) reach anode faster than heavy positive ions can reach cathode

- Photoionization causes the anode to be completely surrounded by cloud of secondary positive ions
- · Cloud "shields" anode so that no secondary negative ions can be collected
- Detector is effectively "shut off"
- Detector recovers after positive ions migrate to cathode
- Dead time limits the number of radiation events that can be detected
 - \bullet Usually 100 to 500 μs
- Continuous Discharge Region
 - Electric field strength so intense that no initial radiation event is required to completely ionize the gas
 - Electric field itself propagates secondary ionization
 - Complete avalanching occurs
 - No practical detection of radiation is possible.

Gas-Filled Detectors

- Most commonly used detection instrument due to versatility
 - Can detect and discern between all types of radiation over entire energy spectrum
 - Cylindrical shape provides the strongest electric field and output current for a given operating voltage
- Most common detectors operate in the ionization chamber, proportional, and Geiger-Mueller regions
- No detectors operate solely in the recombination, limited proportional, or continuous discharge regions.
- Can discriminate between α , β , and γ radiation
 - Pulse height discrimination: electronically filter out pulses below or above expected height for radiation type of interest
- Less sensitive over long range than GM
- Include:
 - Portable neutron radiation survey meters
 - Personnel contamination monitoring
- Include:
 - Area radiation monitors
 - Portable high-range radiation survey meters (Teletector)

Advantages

- · highly sensitive: capable of detecting low intensity radiation fields
- Only simple electronic amplification of the detector signal is required
- · less insulation required to decrease "noise" interference
- Some GM detectors detect γ only
 - Solid casing
- Some detect α , β , and γ
 - α , β radiation: short travel range
 - Cannot penetrate detector casing
 - Mylar window to allow α and β radiation to enter

- α and β can be separately detected by using different window types and thicknesses to filter incident radiation
- Shield must be placed over window to detect γ
 - Blocks α and β

Scintillation Detectors

- Detect radiation by induction of luminescence
 - Absorption of energy by a substance with the subsequent emission of visible radiation (photons)
- Incident radiation interacts with the scintillator material
- Excites electrons in material
- · Electromagnetic radiation emitted in the visible light range
- Common scintillator materials
 - Anthracene crystals
 - Sodium iodide crystals
 - Lithium iodide crystals
 - Zinc sulfide powder
 - Lithium iodide, boron, and cadmium can be used to detect neutrons
 - 6 Steps of Scintillation Detection
- Inside scintillator:
 - Excitation due to absorption of radiation
 - Emission of light photons from de-excitation
 - Transit of light to photocathode inside photomultiplier tube
- Inside photomultiplier tube:
 - Production of photoelectrons in photocathode
 - Multiplication of photoelectrons
- Outside scintillator and photomultiplier tube:
 - Conversion of electronic detector output to useful information
- **Common Scintillator Materials**
- Anthracene crystals
- Sodium iodide crystals
- Lithium iodide crystals
- Zinc sulfide powder
- Lithium iodide, boron, and cadmium can be used to detect neutrons

Photocathode

- Light-sensitive material that absorbs photons and emits photoelectrons
- Common material: Antimony-Cesium
- Emits about one electron for every 10 photons absorbed

Photomultiplier Tube: Dynodes

- Photoelectrons strike successive dynodes and are multiplied (secondary electron production)
- Amplifies the output signal
- If tube has 10 dynodes, total gain would be around 10⁶

• Typical tubes made with 6 to 14 dynodes

Semiconductor Detectors

- Operation similar to gas-filled detectors, but chamber filled with solid semiconductor material
- Crystalline material whose electrical conductivity is intermediate between that of a good conductor and a good insulator
- Benefits compared to other types
 - Very little fluctuation in output for a given energy of radiation
 - Fast
- Energy transfer from radiation to semiconductor target produces a freed electron and an electron vacancy, or hole
- Electrons travel to the anode
- Hole "travels" toward the negative electrode
 - Not physically
 - Successive exchanges of electrons between neighboring molecules in the crystalline lattice

Semiconductor Detectors: Pros/Cons

- Pros
 - Fast response time
 - Due to high mobility of electrons and holes
 - Takes longer for ions to physically travel through space in a gas-filled detector
 - Less statistical fluctuations for any given radiation energy
 - A smaller amount of energy required to produce electron-hole pair in a semiconductor than an ion pair in a gas
 - For a given energy, 8 to 10 times as many charge-carrying pairs are produced in semiconductors as in gases
 - Total charge collected varies linearly with radiation energy
- Cons
 - Very sensitive to heat: must be cooled to eliminate error
 - Photomultiplier output very weak
 - Powerful amplifiers needed in the external circuit

Detection Systems

- Two main components:
 - Detector
 - Gas-filled, scintillation, or semiconductor
 - Measuring apparatus
 - Converts signal output from detector to usable information for the operator
- Detection system categories, by output type:
 - Pulse-type output
 - Mean-level output
- Detection system categories, by application:
 - Nuclear instrumentation
 - Portable survey instruments and area monitors
 - Personal dosimetry
- Pulse-Type Output:

- records a series of individual signals (pulses) separated or "resolved" over time
- each pulse represents a separate radiation event within the detector
- "Frisker"-type survey instruments found near any contaminated area access point

Nuclear Instrumentation (NI)

- NI detectors are used to measure/record neutron (η) flux as a measure of reactor power level
- Range of η flux is wide, spanning from:
 - Shutdown
 - Reactor start-up
 - 100% power
- To accurately monitor η population at all power levels, there are three overlapping detector ranges
 - Source range: $(10^{0} 10^{6})$
 - Intermediate range: $(10^{1} 10^{10})$
 - Power range: $(10^{10} 10^{12})$

NI Detector Ranges

Neutron Energy Ranges

- Fast neutrons have an energy > 1 eV
- Slow neutrons have an energy less than or equal 0.4 eV.
- Hot neutrons have an energy of about 0.2 eV.
- Thermal neutrons have an energy of about 0.025 eV.
- Cold neutrons have an energy from 5x10-5 eV to 0.025 eV.

NI: Fission-Chamber Detectors

- · Neutron detection in source and intermediate ranges
- · Gas-filled ionization-type detector
- Inner "cans" coated with U-235 lining
- Fast neutrons exiting the core are thermalized by the time they make their way inside the F-C detector
 - Interact with materials outside the core
 - Interact with the plastic covering of the detector
- Thermal neutrons lead to fission of the U-235 lining inside the detector
- Reactor core neutron flux is then measured as a product of the fission of U-235 in the F-C detector

Fission-Chamber Output Signal

- Pulse height discrimination implemented in order to pass only the signal portion due to neutron effects
- Pulse discriminator bias: the selective value for pulses
- Products of incident thermal neutrons: fission fragments with average energy of 165 MeV
- Energy of alphas from uranium isotope decay: 4 MeV
- Fission gammas: no more than 7 MeV
- The fission fragment energy due to neutron entering the detector is clearly distinct

 Pulse is much larger than those for non-fission reactions within detector

Pulse Height Discrimination

NI: Power vs. Intermediate Range

- Any power level: reactor produces both neutron and gamma fluxes
- In intermediate range, exact correlation between gamma and neutron flux is not easily predictable
- For an ion chamber to read power in the intermediate range, it must be compensated - Electronically cancel out gamma effects
- In power range, gamma flux becomes insignificant compared to neutron flux
- Gamma compensation no longer necessary

NI: Uncompensated Ion Chambers

• Monitor reactor power in the power range

- Single boron-lined cylindrical chamber operating in the ionization chamber region
- Mean-level output
- Gamma-induced current typically represents only 1% of total output signal

NI: Incore Instrumentation

- · Monitor power production at select locations within the core
- Verify reactor core design parameters: flux mapping
- Data only- no operational plant control
- Simpler version of fission chamber
 - Approx 0.2" diameter, 2.1" length
 - Uses uranium oxide clad in stainless steel, with helium fill gas

NI Detector Circuitry

- A channel consists of a detector, its measuring apparatus (transducer), and a display – Sends signals to the reactor control and protective systems
- At main control panel, reactor core is monitored by
 - Two source range channels
 - Two intermediate range channels
 - Four power range channels (0 to 120% power)
- Third source range channel with dual displays
 - Nuclear instrument cabinet
 - Control room evacuation panel
- Main control panel: U-235-based FC detector
- Instrument cabinet: Boron Triflouride (BF₃) FC detector
- Both are dual-element (dual-can) detectors
 - Provides increased sensitivity in the low η fluxes of the source range
- Pulse height discriminators "screen out" γ flux from η
- Each FC is powered by a high voltage power supply
- Each FC output is amplified and filtered by a separate preamplifier

 Filter electronic noise due to cable lengths
- Preamplifier outputs from 2 FCs are summed at the channel's discriminator
 - Non-neutron pulses are filtered out
 - Signal is further processed and amplified for use as indication of power level

Nuclear Instrumentation: Intermediate Range

- Spans the source $(10^0 10^6)$ and power $(10^{10} 10^{12})$ ranges
- One U-235 fission chamber (can) per detector
- Output signal
 - Pulse-type in the source range
 - Mean-level in the power range

Nuclear Instrumentation: Intermediate Range

- "Pulse pile-up"
 - When passing source and power ranges in either direction, neutron events occur and change so rapidly that less overall sensitivity is needed
 - Gamma flux is not predictably related to neutron flux
 - Cannot be "filtered" by pulse height discrimination
 - Intermediate range neutron flux levels are several orders of magnitude higher than source
 - Pile-up occurs at upper end of detector range due to high magnitude of combined γ and η flux
 - The predictable pulses from the lower end effectively change from an AC signal to a fluctuating DC signal
- Campbell Theorem
 - "With a random occurrence, the variations in the occurrence is proportional to the square root of the random rate."
 - Simply put: by taking the mean value of the oscillations in detector output appearing at the upper-end of the detector scale, a meaningful detector signal is obtained
- Monitored by four independent channels
- Each channel uses a long, boron-lined uncompensated ion chamber
- Each chamber includes two separate neutron detecting sections
- Gammas are so out-numbered by the neutrons that gamma-compensation is not necessary
- One high voltage supply (0-1500 VDC per channel) powers both sections of detector
- Output current from each section is fed to an amplifier
- Amplifier output sent to
 - Protection and control systems
 - Control panel readouts
 - Summing amplifier
 - Add signals from separate detector sections and amplify to make combined signal proportional to total core power (0 to 120%)
- Summing amplifier output sent to
 - Protection and control systems
 - Control panel readouts
- Gammas are so out-numbered by the neutrons that gamma-compensation is not necessary

Power Range Detector Channel Portable Survey Instruments and Area Monitors

Survey meters

- Compact detector systems used to monitor an area for neutrons, beta, alpha, or gamma radiation
- Portable Instruments
 - Survey meter, powered by batteries
 - Can be carried to any remote location
- Area Monitors
 - Survey instruments in permanent installation

Portable Survey Instruments and Area Monitors

Considerations:

- Reduction of size and weight
 - Gas-filled detector produces the most intense output for the lowest applied voltage
 - To reduce the size and weight
 - Reduce battery size: balance between weight and battery life
 - Reducing chamber size: erratic readings, useless
 - A bulky, reliable instrument is preferred to a small one that yields erratic results
- Type, energy, and intensity of the radiation field
 - Low range beta and gamma survey meters
 - High range beta and gamma survey meters
 - Alpha survey meters
 - Neutron survey meters

Low Range β and γ Survey Meters

- Low range: fields ranging from background level to levels of a few hundred milliroentgens per hour
- Most used: Geiger-Mueller tube
- Also used: Scintillation detectors

Low Range β and γ Survey Meters

- G-M tube: Advantages
 - Variety of sizes and shapes
 - Inexpensive
 - The slightest radiation event strong enough to cause primary ionization results in ionization of the entire gas volume
 - Thus detector is highly sensitive, even in lowest intensity radiation fields
 - Only simple electronic amplification of the detector signal is required
 - Hardware lasts longer
 - Requires less power
 - Strong output signal means G-M needs less electrical noise insulation than other detectors

Low Range β and γ Survey Meters

- G-M tube: Disadvantages
 - Incapable of discerning between type and energy of the radiation event
 - Only counts events and yields output in events per unit time or dose rate
 - A beta particle or gamma ray, high or low energy, represents one event counted
 - Only capable of detecting fields to some upper limit of intensity
 - Limited to lower intensity fields due to detector dead time

- Most common G-M gases: noble gases
 - Helium
 - Argon
 - Neon
 - Sometimes hydrogen and nitrogen
 - Characteristics of gas affect dead time
- After primary ionization, avalanche, and output pulse, G-M detector enters phase called tube recovery
 - Positive ions slowly migrate to cathode
 - Neutralized upon arrival
 - Neutralization may result in production of additional electrons and/or photoelectrons
 - Can result in another discharge of the tube, effectively lengthening dead time
- Quenching
 - Process used to prevent multiple G-M tube discharges
 - Methods
 - Electronic circuitry external to detector (inefficient)
 - Quench gases added to the gas volume
 - Self-quenching, efficient
 - Common type: ethyl alcohol, bromine or chlorine
 - Quench gas molecules neutralize positive ions in fill-gas before they can reach cathode
 - · Charged quench gas molecules are then neutralized by cathode
 - Dampens potential for secondary discharge
- G-M tube requires high input voltage
 - Permits strong signal from ion collection
 - Frequent replacement of high voltage batteries
- Detecting beta particles with G-M
 - Particles have short range: window required
 - Mica, mylar, or thin stainless steel
 - Based on window material and thickness, correction factors can be determined to help narrow output to reflect beta activity alone

High Range β and γ Survey Meters

- Most: Uncompensated ion chambers
 - Very simple compared to G-M
 - Pulse or mean-level output
 - Strength of output signal is directly proportional to the # of ion pairs collected
 - Correlates in turn to a function of radiation energy
 - Signal converted to dose rate
- Can detect wide range of field intensities, but...
- Disadvantages of Ion Chambers
 - Output signal weak
 - Must be amplified considerably

- Battery power limitations
- Electronic noise-- frequent zeroing (taring) might be required
- Signal-to-noise ratio renders ion chamber inefficient at low range compared to G-M
- Ion chambers
 - Insulation must be very good
 - Fill gas
 - Air at atmospheric pressure
 - Noble gases
 - For beta, ion chamber must be equipped with a thin wall or window

Alpha Survey Instruments

- A 1.0 MeV alpha particle has a range in air of only ~0.6 cm compared to 330 cm range of beta particles of the same energy in air
- Alpha particle ranges are considerably shorter in denser materials
- Detectors commonly used:
 - Ion chambers
 - · Small field intensities
 - Very thin window must be incorporated
 - Scintillation detectors
 - Very effective
- Scintillation detectors (continued)
 - Commonly sodium iodide (NaI), cesium iodide (CsI), or silver-activated zinc sulfide also
 - Activator materials
 - Desirable "impurities" in scintillator material
 - Capture electrons and holes created through ionization of the scintillator and to emit the light photons upon returning to ground state
 - Examples
 - Silver in zinc sulfide
 - Thallium in sodium and cesium iodides

Neutron Survey Instruments

- Neutrons alone do not produce ionization (a detectable signal)
- The detector must contain a material with which the neutron interacts to produce ions
- Most common target material: Boron
 - Either as a fill gas or a coating on the inner wall
- Survey meters used for neutron detectors
 - Gas-filled
 - Semiconductor
 - Scintillation
- Common setup for gas-filled portable neutron survey meter
 - BF₃ proportional counter surrounded by a cadmium loaded, polyethylene sphere
 Sphere thermalizes incoming fast neutrons so they can be detected
 - Meter output can read directly in millirem or rem per hour
- Ion chambers as neutron survey instruments
 - As with NI, commonly use boron-10 coating

- Must be compensated for gamma
- Scintillation detectors as neutron survey instruments
 - Common material: lithium iodide
 - Thermal neutrons interact with lithium to form tritium and an alpha particle
 - Alpha particle causes measurable ionization

Portable Radiation Survey Instruments

- Pre-operational checks:
 - Battery-check: battery strength should be well within the acceptance range
 - Calibration check: a sticker affixed to the side of the instrument notes the "calibration due date"
 - Visual inspection: inspect for no visible signs of damage (i.e. loose, or missing parts; damaged detector; cracked meter face, etc.)
 - Source check: expose the detector to the "check source" [either internal or external] and note the meter response. It shall respond within the set "acceptance range"
- Pre-operational checks:
 - Zero-check: adjust so that the meter reads zero (0) when unexposed to a source
 - Light-check: applicable to a scintillation detector, the meter should read zero (0) when no source is present. Spurious counts are indicative of a damaged detector (i.e. light is leaking into the detector)

Pocket Ion-Chamber Dosimeter

- Self-reading
- Records dose in either milliroentgen (mR) or Roentgen (R)
- · Sensitive to gamma only
- DC voltage applied to quartz fibers inside the chamber
- As gamma interactions/ionizations occur within the chamber, and the ions are collected, the coulombic repulsion is decreased, and the fibers move closer together
- Extremely sensitive to shock
- Located in Emergency Kits

Electronic Dosimeter

- · Activated using the Electronic Dosimeter reader
- Self-reading, digital display of accumulated dose and dose rate
- Records accumulated dose and "highest dose rate field" in milliroentgen (mR) and milliroentgen per hour (mR/hr), respectively (can be set to record in units of Roentgen)
- Visual and audible alarms for accumulated dose and dose rate
- Silicon diode detector to detect gamma radiation (sensitive to gamma only)
- Resistant to shock
- Downloads dose and dose rate data to Radiation Exposure Control database when deactivated by the ED reader

Thermoluminescent Dosimeter

- Scintillation-type device
 - Lithium Flouride (LiF) or Calcium Flouride (CaF)
- CaF: high efficiency for detecting gamma and "X" radiation poor at detecting neutrons
- LiF: capable of detecting alpha (α), beta (β), gamma (γ), "X" and neutron (η) radiation typically used at nuclear power plants

- As incident radiation interacts with the crystal, the resultant ionization/excitation energy is stored.
- Crystal retains this energy until heat is applied.
- The "trapped" energy is then released in the form of light, as the atoms of the crystal return to their "ground state"
- The light emitted is then correlated to dose received
- Once the TLD has been "read", memory is cleared
- TLD is then available for re-use