Competency 1.5 **Radiation Protection personnel shall demonstrate a working level knowledge of the principles and use of radiological instrumentation and radiological monitoring/survey practices.**

1. SUPPORTING KNOWLEDGE AND/OR SKILLS

a. Describe the principle of operation of gas-filled detectors.

b. Discuss the following for gas-filled detectors:
   - Voltage-response curve (i.e., six region curve)
   - The three regions useful for radiation detection and measurement
   - The sequence of events that occur following an initial ionizing event in an Ionization Chamber, a Proportional Counter and a Geiger-Müeller Detector

c. Describe the principles of operation of scintillation and solid state detectors.

d. Describe the principle of operation and application of nuclear spectroscopy

e. Discuss the purpose, principles of detection and operation, and field application of the following:
   - Continuous air monitors (CAM)
   - Airborne radioactivity samplers
   - Area radiation monitors (ARM)
   - Criticality detection/alarm systems
   - Personnel contamination monitors
   - Process radiation monitors

f. Discuss the basic elements and applicable standards of a radiological instrument calibration program, including the following:
   - Calibration source selection and traceability
   - Source check and calibration frequency
   - Instrument energy dependance

g. Discuss the following concepts as they relate to radiological counting measurements:
   - Background
   - Lower limit of detection
   - Minimum detectable activity
   - Counting efficiency
   - Counting uncertainties

h. Describe various radiological situations and the use of appropriate radiological surveys including: radiation, contamination, and airborne radioactivity surveys.

2. SUMMARY

Operation of Gas Filled Detectors

Almost all radiation detectors detect charged particles that are created as a result of ionizing radiation interactions with matter. In a gas filled detector, a gas, such as air, is used as the detecting medium and is housed in a chamber. As gamma radiation interacts with the detector housing material or directly with the air molecules, recoil electrons are generated which enter the fill gas. These recoil electrons, called primary electrons, cause hundreds or thousands of ionizations and excitations of the neutral air molecules creating secondary electrons or ions. Ionization of an air molecules produces electrical charges, a large positive ion and a light negative electron. Together they are called an ion pair.

In order to detect radiation, the ion pairs created by ionization must be collected. Collection is accomplished by the use of a polar electric field. In a gas filled detector the outer wall is usually negatively charged, attracting the large positive ions. In the center of the chamber lies a wire or plate that is positively charged attracting the electrons. Voltage is applied between the anode wire and the cathode wall, providing the force to accelerate the charged particles from their point of origin to the opposite poles. Due to the difference in masses, the light electrons accelerate hundreds to thousands of times faster than the large positive ions. If the voltage is great enough, the secondary electron attains sufficient kinetic energy to ionize neutral air molecules during a random collision, creating tertiary electrons. This creation of many tertiary ions from a single secondary ion is called gas amplification. Thousands of tertiary electrons accelerate and are collected at the anode before the massive positive ions have begun to move. The result is the build up and presence of a positive ion cloud which weakens the electric field strength in the detector below the gas amplification threshold, terminating the process.

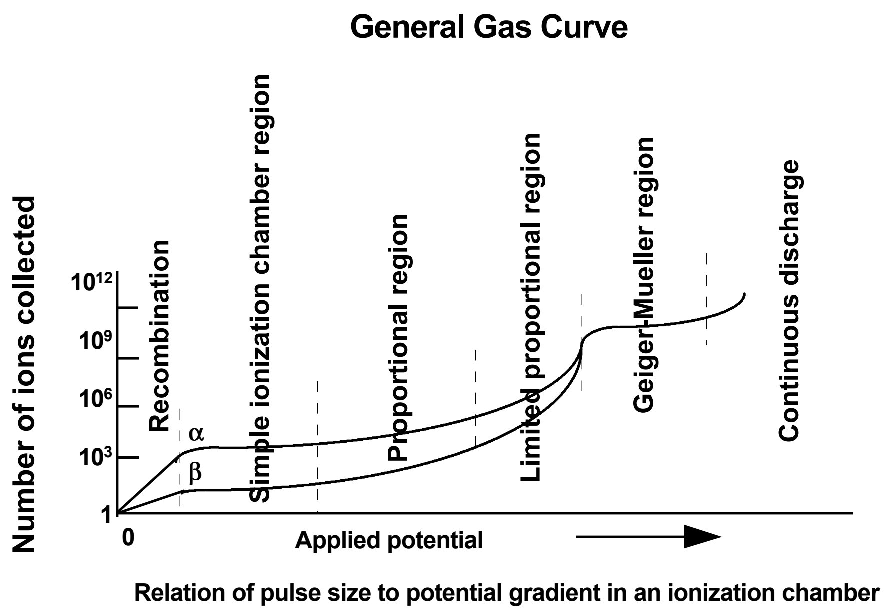
The collection of the ion pairs produces a current or an electrical pulse depending on the design of the instrument. Current mode is useful in quantifying the intensity of a gamma radiation field and the pulse mode is useful in qualifying or analyzing the type and/or energy of the radiation. Which mode the instrument is used in depends on the needs of the user.

Gas Filled Detectors

Six Region Curve

The figure below graphs the pulse height of ion pairs collected versus the applied voltage. As can be seen from the graph, as the voltage increases, the number of ion pairs collected also increases, but not in a directly linear fashion.

Of the six regions identified on this graph, only three are used for radiation instrumentation, they are the ionization, proportional, and Geiger-Müeller regions.



Recombination Region

In this region, the electric field strength is not consistent enough over the entire volume of the detector to collect all the ion pairs created by radiation. Some ion pairs are able to recombine, due to opposite charges attracting, before collection can take place. As the voltage increases over this region, the ion pairs are accelerated at a faster rate and a higher percentage of the ion pairs formed are collected. Over most of the recombination region, not all of the ions pairs created are collected which results in a loss of valuable information. Therefore, the recombination region is not used for survey equipment.

Ionization Chamber Region

In order to prevent recombination, the electric field strength is increased by increasing the voltage. When voltage is increased past the recombination region, a point is reached where all the ion pairs formed in the chamber are being collected. This is the ionization region. Small increases in voltage have no effect on pulse size within this region. If pulses occur at frequent intervals, a steady current can be measured instead of just counting pulses. This current is directly related to the rate at which ion pairs are being formed, and can be related to an exposure rate. Ion chamber-type dose rate meters operate in this region of the curve and the current levels being measured are typically in the range of about 10^{-8} amperes. Examples: Eberline RO-2 and RO-7, Victoreen Cutie Pie and 470A Panoramic.

Proportional Region

As the voltage on the detector is increased beyond the ion chamber region, the ions created by primary ionization are accelerated by the electric field towards the electrode. Unlike in the ion chamber region, the primary ions, specifically electrons, in the proportional region accelerate towards the anode gaining kinetic energy and collide with neutral air molecules along the way. A point is reached where the electron energy exceeds the ionization potential of air molecules and collisions produce secondary ionization or ion pairs. These newly formed secondary ions are also accelerated, causing additional ionizations. The large number of events, known as an avalanche, creates a single, large electrical pulse. This effect is known as gas amplification, which is a ratio between the primary ions produced and the number of ions collected. The gas amplification factors (GAF) can be 10^6 or more,

$$GAF = \frac{number\ of\ ions\ collected}{number\ of\ initial\ ions}$$

The output pulse is now very large, but is proportional in size to the number of ion pairs initially formed. As a result the proportional region can analyze the energy of a particle or photon and identify the type of radiation and/or the specific radionuclide.

The proportionality or GAF is highly dependent on applied voltage. Slight changes in voltage can alter the GAF, hindering the instruments ability to discriminate between the different types of radiation.

Limited Proportional Region

Additional increases in voltage beyond the proportional region result in the gas amplification factor losing its proportionality to the initial pulse size. The ability to differentiate between radiations is lost. The output pulses from alphas and betas are becoming identical in size. The limited proportional region is not used for radiation detection.

Geiger-Müeller (G-M) Region

A point is reached where higher voltage supplies each ion created in the tube with sufficient energy to cause an ionization “avalanche.” All pulses are of the same size, regardless of the type of radiation which initiates it. Once the cascade of ionizations has started, it continues along the length of the detector centerwire.

The positive ions move to the cathode chamber wall for collection, and upon colliding with the wall, can emit free electrons which are energetic enough to continue the avalanche. To prevent a continuous avalanche, a quenching agent is added to the gas as a charge transfer mechanism. The quench gas accepts the positive charge from the positive ion and transfers the positive charge to the detector wall without releasing free electrons.

During the time it takes the positive ion cloud to move to the wall, the electric field strength in the tube is weakened, and another pulse cannot form. This is dead time. As the field builds back up, small pulses can form, but may not be large enough to be detected by the pulse counter. The overall time from the start of one ionizing event until the next detectable event is termed resolving time, and is typically 50 to 150 microseconds (μsec). Events which occur during the resolving time will go undetected. This places an upper limit on the count rate at which G-M tubes can operate without resolving time correction.

Continuous Discharge

If the voltage is sufficiently high, there is a continuous arc across the electrodes and the tube will go into continuous discharge. This region is totally useless for measuring radiation.

Ionization Chambers

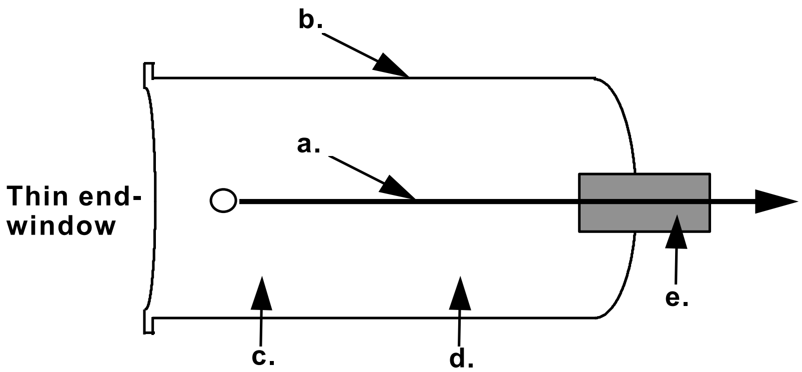
Ionization chambers operate in the ionization chamber region (region 2) of the general gas curve. Characteristics associated with these detectors include:

- Operate in current mode
- Air is typically used as fill gas
- Gas amplification (multiplication) not required for operation
- Fairly rugged devices
- Short warm-up times (<1 minute)
- Primarily designed to measure x-ray and gamma ray radiations
- Typical readout in units of milliroentgen per hour (mR/hr) or roentgens per hour (R/hr)
- Slow response (relatively insensitive devices)
- Ideal for exposure rate measurements; can measure very high radiation levels with virtually no dead time
- Flat energy response above 100 kiloelectron volts (keV)
- Sensitive to temperature, pressure, and humidity conditions
- Detector can "leak" current; most designs require a "zero" strip adjustment
- Can detect/measure alpha and beta radiations with appropriate calibration factors and/or instrument design.

Geiger-Müeller Detectors

G-M detectors are widely used instruments for the detection of ionizing radiation. These detectors, often referred to as Geiger or G-M counters, are one of the oldest radiation detection devices in existence. A G-M detector, as previously noted, is a gas-filled detector operated in the G-M region (region 5) of the general gas curve.

All Geiger detectors share certain design features. The diagram below depicts an "end window" G-M tube with key components labeled. A brief description of each follows.



a. Anode - A positively charged central wire, typically composed of tungsten, with a diameter on the order of 0.003 to 0.004 inches. Tungsten is favored for its strength and uniformity The anode is typically a straight wire, but wire loop anodes are found in other designs (e.g., “pancake” detectors).

b. Cathode - The outer envelope and conducting surface, negatively charged with respect to the anode. It is usually composed of metal (steel or nickel) and, on occasion, glass that requires an inner conductive coating.

c. Fill Gas - A noble gas that occupies 90 to 95% of the active volume of the detector. The noble gas is typically helium, neon, or argon.

d. Quench Gas - A gas occupying 5 to 10% of the detector volume. The quench gas functions to prevent the formation of spurious pulses.

e. Insulator - Prevents arcing inside the detector.

High voltage applied to the detector allows the collection of ion pairs--electrons are collected at the anode while positively charged gas molecules migrate to the cathode. The detector usually operates below atmospheric pressure.

To understand the operation of a G-M counter, it might be useful to consider the steps involved in the production of the geiger discharge that creates pulses of uniform size.

Step 1: Ionizing radiation enters the detector and strips an electron from a neutral fill gas molecule, creating an ion pair.

Step 2: Due to the high electric field (high voltage), the “free” electron accelerates toward the anode. As it does so, it acquires sufficient energy to create secondary ionizations. These secondary ionizations serve to dramatically amplify the number of electrons arriving at the anode. This initial amplification is called the Townsend avalanche (the avalanche created by a single original electron).

Step 3: A series of avalanches follows in rapid succession, propagated by photon emission created by the excitation and subsequent de-excitation of electrons that were not ionized. The wavelength of these photons is in the visible or ultraviolet region.

Step 4: The anode becomes completely enveloped with electrons indicating a geiger discharge has occurred.

The geiger discharge is formed in approximately one microsecond (μsec) following the initial ionization in the detector. Because the same number of avalanches (statistically speaking) are created each time during this process, the output pulse represents the same amount of collected charge. Therefore, the pulse's height or amplitude remains constant and no energy discrimination is possible.

One of the most significant disadvantages associated with G-M counters is their so-called "dead" time, a period in which the tube does not respond to radiation. It is caused by the slow movement of the positive ions away from the anode; the electric field intensity is too low to produce a geiger discharge.

There are three principal types of G-M counters that are routinely used in health physics:

- End Window
- Side Wall
- Pancake

Principal Type	Description
End Window	The radiation enters the sensitive volume of the detector by passing through a very thin mica window (thinner than a piece of paper) attached to the end of the detector. The window may be protected by a mesh screen. Thin end windows are capable of detecting alpha, beta, and gamma radiations under the appropriate conditions and with proper survey techniques.
Side Wall	This detector has a sliding sleeve that opens and closes from the side. Higher energy beta particles (~ 300 keV and above) and gamma rays can be detected with the window open; closing the window eliminates the beta contribution and that of lower energy photons.
Pancake	A pancake G-M is similar to the end window in that a very thin mica covering is used. Its design offers a greater detection area than the end window probe in addition to having the same capability of detecting a variety of commonly encountered radiations.

G-M detectors have a wide variety of uses. As a general comment, however, it must be mentioned that because all pulses from a G-M counter are of the same amplitude, no energy discrimination is possible (no spectroscopy). Geiger counters do not respond with equal count rates to equal exposures rates from photons of differing energies. Therefore, they are best suited to count rate determinations rather than measurements of exposure, exposure rate, activity, etc. Geiger counters are detection instruments first and foremost. That having been said, some specific applications now follow.

- Contamination Surveys - Fairly rapid monitoring of personnel (hands, clothing, etc.), equipment (tools, etc.), and laboratory surfaces (benches, tabletops, hoods, etc.) can be accomplished using a variety of G-M detectors. When surveying for soft beta emitters, e.g., carbon-14 (C-14), sulfur-35 (S-35), calcium-45 (Ca-45), phosphorus-32 (P-32), a thin end window or pancake detector would be required. Higher energy beta and gamma emitters could be detected with end window, pancake, and side wall G-M detectors. These surveys and the detectors involved can be utilized in both laboratory and field applications.

- Leak Testing - Leak testing is a procedure designed to determine whether any removable activity above a specified value is present on the outer surfaces of a sealed source. A smear is taken on the outer surface and counted in a G-M detector. The resulting count rate, with background subtracted, is a measure of the removable activity. If the efficiency of the detector is known, count rates can be converted into disintegration rates for comparison with the guideline value. This procedure is often followed for industrial radiography sources where the opening (port) that the source passes through is smeared with a Q-tip and counted as described above.

- Accident Dosimetry - Geiger counters can be used for estimating the neutron dose from the activation of sodium-23 (Na-23) to Na-24 in the blood. A pancake probe, for example, is placed either against the abdomen of the individual as he/she bends over or under the armpit. Any measurable increase in the count rate (over background) can be an indication of a significant neutron dose. This procedure is referred to as the quick sort method because it can rapidly screen individuals following an accident. The procedure is based on detecting gamma rays emitted from the decay of Na-24.

- Exposure Rate Measurements - In general, measurements of exposure rates can cautiously be performed under two circumstances: when (1) the accuracy of the results is not a crucial concern; and (2) the instrument is calibrated for the same energy that will be encountered in the field or laboratory.

A variety of G-M counters can be used for exposure rate measurements (keeping in mind the caveats noted above). These include the typically encountered end window, side wall, and pancake designs. In addition, modified detectors are also available. For example, an energy-compensated side wall G-M tube consists of a rubber sleeve which slides over the tube to flatten the photoelectric response of the detector. Depending on the probe design, exposure rates of up to several R/hr can be measured. A telescoping detector is also available; in this design, a probe containing two halogen-quenched G-M tubes can be extended up to approximately 14 feet from the user and the readout device. Exposure rates of up to 1,000 R/hr can be recorded while the surveyor's dose is dramatically reduced by utilizing distance. This particular G-M detector has practical applications in several areas: radioactive waste surveys, monitoring irradiated fuel storage and transport, monitoring the removal of irradiated samples from reactors, reducing exposure to personnel when locating and evaluating radioactive sources of unknown strength, and emergency radiation accidents.

Typical advantages and disadvantages of GM detectors are noted below.

Advantages:

- Fairly reliable
- Ease of operation
- Wide variety of shapes and sizes
- Relatively inexpensive
- Highly sensitive (one ion pair can produce a discharge)
- Large output pulses (>1/4 volt to several volts)
- No external amplification normally required due to large amplification factors inherent in the operation of the detector (minimal electronics)
- Used in field and laboratory settings
- Detect a wide variety of radiations including alpha, beta (soft and hard), x-ray, gamma, and cosmic (high energy gammas)
- Choice of proper operating voltage allows for reproducible results even if the voltage varies
- Excellent for low-level counting rate surveys including personnel and equipment monitoring, leak tests, and as a quick screening method in accident situations
- Halogen tubes have technically infinite lifetimes
- Exposure rate measurements possible under proper conditions

Disadvantages:

- No energy discrimination (spectroscopy is not possible)
- Principally detection, not measurement, devices
- Quenching required to eliminate multiple pulsing
- Worst resolving times of any gas-filled detector
- Slope of the plateau must be kept reasonably flat for reproducible results
- Organic tubes have limited lifetimes
- Self-absorption in the counter wall and window is possible for alpha and beta radiations
- Efficiency is quite poor for gamma rays (approximately 1%)
- Without antisaturation circuits, detector can saturate in high radiation fields and read lower than the true value or even "zero"

Proportional Counters

Proportional counters are extremely versatile instruments used for the detection of ionizing radiation. They share certain design features. Various key components are described below.

Anode - Typically composed of tungsten, with a diameter of approximately 0.001 inches. The anode either takes the form of a loop or straight wire. The nature of gas amplification in a proportional counter requires an extremely uniform central wire.

Cathode - The outer envelope and conducting surface, negatively charged with respect to the anode, and usually composed of steel.

Fill Gas - The gas that occupies the sensitive volume of the detector. It may be an inert gas (argon, krypton, xenon) or a hydrocarbon (methane, ethylene). Other gases are used depending on the application. A very common proportional gas, known as P-10, consists of a mixture of 90% argon and 10% methane. The methane serves as a quenching agent.

Insulator - Prevents arcing inside the detector.

A proportional counter operates in the proportional region (region 3) of the general gas curve where the applied high voltage is sufficiently high to create secondary ionizations. In contrast to G-M counters, where all pulses are of the same amplitude, the size of the pulse in a proportional counter is proportional to the initial number of ion pairs produced in the detector volume.

When ionizing radiation enters the sensitive volume of a proportional counter, ion pairs are created. The free electrons that are initially produced accelerate toward the anode; secondary ionizations result from the potential applied to the detector. This is known as gas amplification. The number of electrons that arrive at the anode constitute an avalanche (Townsend avalanche). In these respects, proportional counters are similar to G-M counters. Here the similarities end, however. Geiger counters operate with amplification factors on the order of one billion (10^9); a series of avalanches eventually envelopes the entire anode, producing pulses of uniform size. In contrast, proportional counters rely on much lower amplification; values in the one thousand (10^3) to one hundred thousand (10^5) range are typical. The anode does not become saturated with electrons and the pulse height is proportional to the initial number of electrons produced in the gas. Energy discrimination with the ability to distinguish radiations becomes possible.

Proportional counters are known for their short dead times. These counters have the capability to distinguish two pulses (two separate ionizing events) in a short period of time. Since each avalanche is restricted to a short section of the anode, unlike G-M counters, the counter can clear this avalanche and respond to a new ionizing event in a time frame approximating 0.5 to 5 μsec. This is a decided advantage when high counting rates are involved.

A variety of counters operating in the proportional mode exist for routine and specialized applications. Two of the more common examples are:

- Air Proportional - These counters respond only to alpha radiation. Alpha particles enter the detector through a thin window of aluminized mylar. The fill gas is air instead of a noble gas. These lightweight, portable counters are useful for contamination surveys but must be used with caution in areas of high humidity. For this reason, they are most often encountered in the western half of the United States, where humidities are lower and the response of the detector is not adversely affected.

- Gas Flow Proportional (field use) - These portable instruments respond to both alpha and beta radiation through the appropriate selection of operating voltage. In one design, the fill gas (often liquid propane) is contained in a small canister inside the instrument housing; gas is fed from the canister through a teflon tube housed inside an electrical cable to the probe. The canister is usually replaced every four to six hours. Other designs utilize larger canisters (often P-10 cylinders) as the source of the counting gas. The counter can be purged of air and operated as a stand-alone unit if desired.

- Gas Flow Proportional (laboratory use) - Proportional counters in a laboratory setting often require the use of large gas cylinders and lead shielding (to reduce background), which limits their portability. The counter can be configured to allow radiation from the source to directly interact with the fill gas, eliminating the need for a thin entrance window. The design is appropriately called a windowless gas flow counter. Thin entrance windows can also be used; however, corrections for self-absorption must be applied. The counting geometry is such that in a hemispherical arrangement all the radiation emitted from the surface of the source or sample can be detected. This is known as 2π (pi) geometry, which infers counting efficiencies of 50%. A 4π geometry is also possible whereby the source backing is thin compared with the range of the radiation. Radiations can then be detected from all directions, with efficiencies approaching 100%.

Common applications associated with proportional counters include:

- Contamination Surveys - Detection of alpha and beta radiations can be performed with portable instruments (air proportional and gas flow counters). Large floor surfaces, for example, can be rapidly screened for contamination using a portable, multiwire anode gas-flow counter with a 600 cm^2 effective surface area. The floor monitor can be moved over the area of interest to quickly identify contaminated locations. Follow-up surface contamination measurements can then be performed with other field proportional counters or another instrument of choice.

- Neutron Detection - Detection of slow neutrons can be accomplished using pulse height discrimination. In a very common reaction, boron trifluoride gas interacts with slow neutrons to produce alpha particles. The alphas are counted while gamma rays are rejected based on their respective pulse heights. The neutrons are detected indirectly by the formation of alpha particles. Other proportional gases are routinely used to accomplish the same objective. The counter can also be modified through the use of moderators to detect fast neutrons.

- Assay of Alpha, Beta, and X-ray Sources - Proportional counters can be used to assay (measure) source activities under the proper conditions. The thickness of the source and source backing must be considered in terms of absorption, especially for alpha and beta radiations.

Typical advantages and disadvantages of proportional counters follow.

Advantages:

- Versatile instruments (wide variety of applications)
- Variety of shapes and sizes available
- Highly sensitive (counter can respond to the formation of one ion pair)
- Size of pulse proportional to initial number of ion pairs
- Can detect (directly or indirectly) a variety of radiations: alpha, beta, gamma, x-ray, and neutrons
- Can distinguish radiations (alpha, beta, etc.) based on pulse height discrimination
- Energy discrimination (spectroscopy)
- Ability to count at much higher rates, relative to G-M counter, because of excellent resolving times (0.5 to 5 μsec)
- Not only detection, but measurements of dose and dose equivalent possible
- Used in field and laboratory setting

Disadvantages:

- Stable high voltage required due to nature of gas amplification
- External amplification (preamplifiers, amplifiers) required to produce pulse of sufficient size for detection
- Generally more expensive than geiger counters
- Proper operation requires more attention on the part of the user
- Instruments tend to be "finicky" (i.e., more attention to maintenance is required [not as reliable as G-M counters])
- Susceptible to environmental conditions (heat, humidity)
- Self-absorption possible in counters employing entrance windows
- Efficiencies are poor for higher energy x-rays and gamma rays

Operation of Scintillation Detectors

When irradiated, some materials become "excited" and return to a ground state by emitting photons in the visible light spectrum (e.g., radium watch dials). This forms the basis for the scintillation detectors. A variety of materials, including zinc sulfide, sodium iodide (NaI) crystals, stilbene, and special plastics can be used, depending on the application. All utilize some type of photomultiplier tube (PM tube) to convert the light pulse into an electrical pulse.

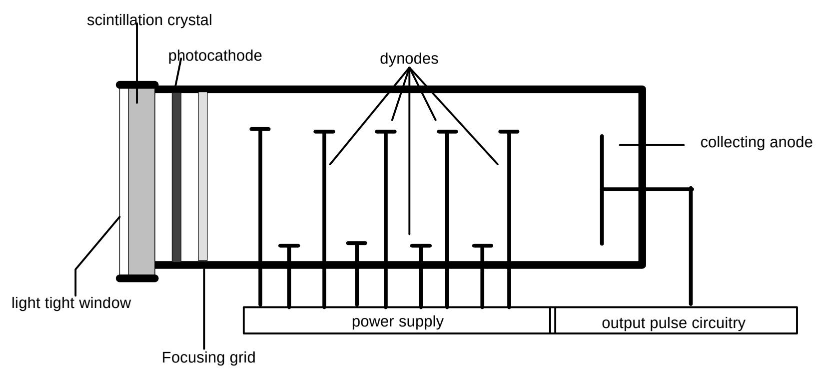


Figure 2, Scintillation Detector

The scintillator can be enclosed in a variety of housings, depending on the application and radiation(s) to be detected. All must be light tight or installed in a light tight detector assembly to prevent stray light from entering the PM tube. For beta and alpha detectors, a thin, opaque window, such as aluminized mylar, keeps ambient light out, but permits the radiation to enter. The scintillation medium is excited by the ionizing radiation, and upon returning to a ground state, emits a pulse of light. The size of the light pulse is determined by the amount of energy deposited in the event. The light pulse enters the PM tube through an optical window and strikes the photocathode, which in turn releases a few electrons. The electrons are drawn to a high-voltage electrode, called a dynode. Each electron that hits the dynode causes a few more electrons to be released. The process is repeated a number of times, with the result being a large pulse which is collected at the anode. Since the number of electrons initially released by the photocathode is directly related to the size of the light pulse, the process can be used to differentiate events of varying energy. This forms the basis for a scintillator-based nuclear spectroscopy system. Although scintillation detectors can be used for alpha and beta radiation, they are primarily used for gamma detections.

Another type of scintillation detector is the liquid scintillation counter (LSC) in which the sample to be counted, usually a wipe test, is physically placed inside a small vial with a scintillation "cocktail." The cocktail is a solution made up of a solvent and scintillating solute (e.g., toluene, dioxane, or a non-toxic solution). With LSCs, the solute in the cocktail absorbs the decay energy from the solvent and re-emits the energy as light to be collected by the PM tube and output electronics system. Because of its sensitivity, the LSC is often used for measuring lower energy beta emitters such as tritium (H-3), carbon-14 (C-14), sulfur-35 (S-35), and phosphorus-32 (P-32). Higher energy beta emitters such as P-32 can also be assayed by this method. In recent years, the use of LSC for counting and quantifying alpha emitters has markedly increased. Gamma emitters, however, are not normally assayed by this technique.

LSC is a specialized/sophisticated laboratory technique for assaying (quantifying) principally low energy beta emitters. It is not ordinarily used for identification of radionuclides unless the spectrum is simple in nature. LSC has several advantages including the lack of sample self-absorption or backscatter, good geometry, and good efficiencies (up to 100%). Applications include counting and analyzing water and urine bioassay samples, air filters, vegetation, animal tissue, and waste material. Site screening and cleanup associated with DOE remediation projects can be expedited. Alpha and beta counting can now be done simultaneously. Principal disadvantages have historically included the problems of luminescence (more light emitted than desired) and quenching (loss of the light signal).

Operation of Solid State Detectors

A good conductor is a material that allows the flow of electrical current. An insulator is a material that prevents the flow of electrical current. The number of electrons in the outer shell dictate whether an atom will be a conductor or insulating type material. Conductors have one or two electrons in the outer shell, while insulators have close to eight outer shell electrons. A semiconductor material falls some where in between a conductor and an insulator. For example, two semiconductor elements used for radiation detection are germanium and silicon and both have four outer shell electrons.

There are two types of semiconductor materials, P and N. P-type materials tend to give up electrons to other atoms, leaving "holes" in the atoms electronic crystalline structure, and become positively charged. N-type materials tend to accept electrons, filling in any available holes in the electronic structure, and develop an overall negative charge.

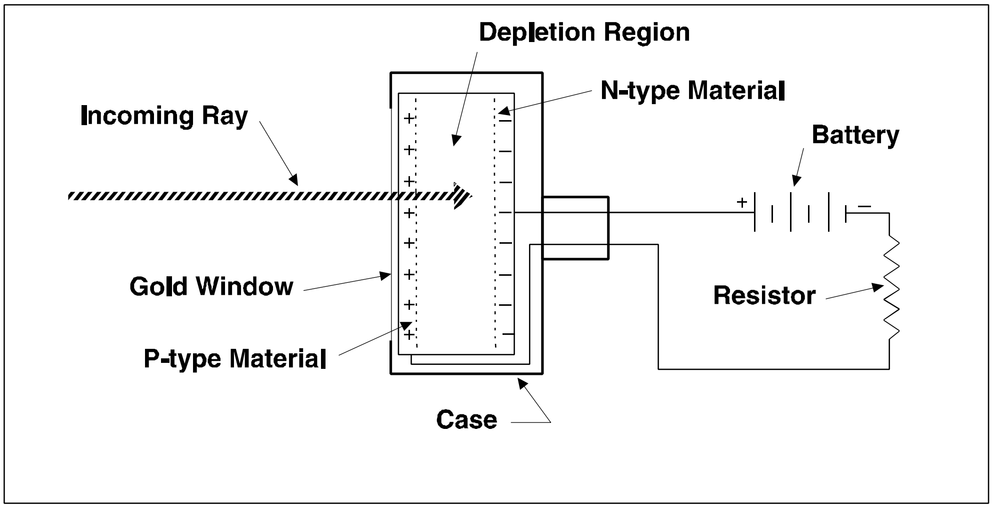


Figure 3, Solid State Detector

Germanium and silicon both have ridged crystalline structures that allow the transfer of electrons to holes in the crystalline structures of adjacent atoms. A radiation detector can be made by taking advantage of semiconductor properties by laminating a P- and N-type material together and applying a high voltage through the material with the negative pole or cathode on the P- type material, and positive pole or anode against the N-type material. This electrical field orientation, called reverse bias, will force electrons to migrate and collect at the anode and at the same time the holes will be developed in the opposite direction towards the cathode. The region in between the two poles will be depleted of free electrical charges, which is very analogous to air molecules in a gas-filled detector. As radiation is deposited in the material, free electrons are liberated and immediately collected. This creates a pulse whose size is dependent on the energy of the incoming radiation. This feature allows semiconductor detectors to be used in an analytical instrument to identify radionuclides when connected to a multichannel analyzer and a computer library.

Nuclear Spectroscopy

The identification of radionuclides is important for health and safety and regulatory compliance reasons. Two methods commonly used to identify radionuclides are by half-life, type, and energy of the radiation(s) emitted. Nuclear spectroscopy is the analysis of the type and energies of radiation emitted to identify the radionuclide. A spectroscopy system separates pulses from a scintillation or semiconductor detector. The spectrum provides detailed information useful to identify unknown isotopes. An example of a spectrum analysis is given in Figure 4. As is evident in Figure 4 germanium lithium (GeLi) solid state detectors provide much more distinct spectra than sodium iodide (NaI) scintillation crystals.

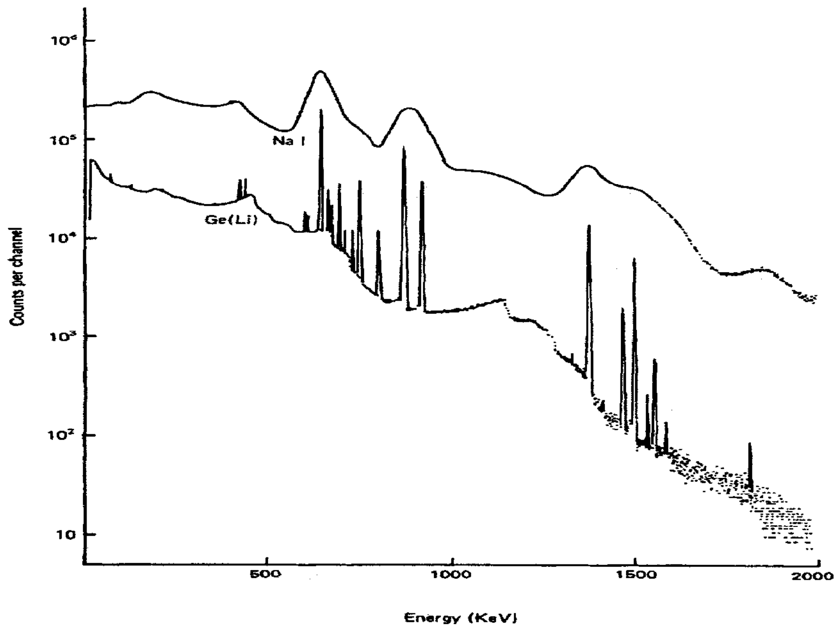


Figure 4, Spectrum Analysis

<u>Principle of Operation</u>

Gamma and alpha radiation emitted from the nucleus during decay are monoenergetic, meaning there is only one discrete energy. The decay energy is characteristic of that radionuclide, like a finger print. When a sample is analyzed, that discrete decay energy must be deposited in the active volume of the detector and create an electrical charge. The electrical charge must be collected over a small period of time and attributed to the decay of a single atom. If this occurs, the result is an output pulse that is proportional to the decay energy and provides identification of the radionuclide. The calculation of a pulse is demonstrated below. The electrical charge in a gas proportional detector can be calculated from the following given information:

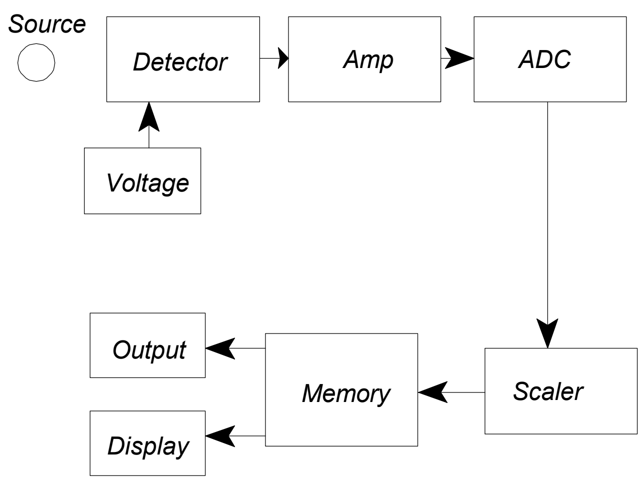
Given:

Radiation emitted	=	alpha
Decay Energy	=	5 MeV
W value of the gas	=	30 eV per ion pair
Electrical charge per ion pair	=	1.6×10^{-19} coulombs per ion pair
Gas amplification factor	=	1,000

The electrical charge or pulse size in coulombs is calculated as:

$$= \left(\frac{5\ MeV}{1}\right)\left(\frac{1x10^{6}\ eV}{1\ MeV}\right)\left(\frac{1\ ion\ pair}{30\ eV}\right)\left(\frac{1.6x10^{-19}\ coulombs}{ion\ pair}\right)\left(\frac{1{,}000}{1}\right) = 2.6x10^{-11}\ coulombs$$

A spectroscopy system consists of the detecting system with its power supply, a linear amplifier and pulse shaper, a single or multichannel pulse height analyzer, and the display system. The system has three functional segments: an analog to digital conversion, which converts pulse amplitudes to digital numbers; a memory with a number of registers, to add up the number of pulses in each channel; and an input/output section, which allows display or printout of the data. The choice of a certain detector system determines the type of radiation to be handled. The following figure presents a block diagram of a multichannel analyzer.



Application

Nuclear spectrum analysis systems are generally used in laboratory settings for the identification of radionuclides in a given sample. In some cases these instruments are portable but may be cumbersome to handle.

In many cases radiological postings, requirements, effluent discharges, radwaste, and internal dose limits require that specific radionuclides be identified. Some instrumentation used in spectroscopy systems and their specific uses are given in the chart below.

Radiation	Analytical Instrument	Type of Instrument
Alpha	• Surface Barrier Detector • Gas flow Proportional • Liquid Scintillation	- Silicon Solid State - Gas-Filled - Scintillation
Beta	• Liquid and Plastic Scintillation • Surface Barrier Detector	- Scintillation - Silicon Solid State
Gamma, X-rays	• Sodium Iodide (NaI) • High Purity Germanium (HPGe) • Germanium Lithium (GeLi) • Silicon Lithium (SiLi)	- Scintillation - Solid State - Solid State - Solid State

Radiation Instrumentation Applications

DOE 10 CFR 835, *Occupational Radiation Protection*, requires monitoring of individuals and areas under Subpart E - Monitoring in the Workplace. Section 835.401 offers several valid reasons why such monitoring must be performed. Among these are the:

- Documentation of radiological conditions in the workplace.
- Observation of changes in radiological conditions.
- Detection of a general buildup of radioactive material.
- Verification of the effectiveness of engineering and process controls.
- Identification and control of potential sources of personnel exposure to radiation and/or radioactive materials.

The DOE *Radiological Control Manual* offers detailed guidance for implementation of radiation protection in the DOE system. It establishes practices for the conduct of radiological control activities and states DOE's position and view on the best course of action currently available in the area of radiological controls. Chapter 5, Part 5 discusses radiological monitoring and surveys.

NOTE: This manual is intended to be reissued as a RadCon Technical Standard. The use of “shall” statements presently in the document will presumably be changed to "should" (or equivalent) statements. Regarding this radiation protection competency, statements referenced from the DOE *Radiological Control Manual* employing the word "shall" have been modified to "should" or similar wording to reflect the shift of this manual from a regulatory-based document to a guidance document.

DOE issued a series of implementation guides (IGs) covering a variety of radiation-related topics. The IGs are designed to provide acceptable methodologies that comply with 10 CFR 835. The implementation guide entitled *Workplace Air Monitoring* (G-10 CFR 835/E2- Rev. 1) offers detailed guidance in this topical area. For the purposes of this competency, information provided regarding CAMs is particularly relevant.

DOE/EH-0173T, *Environmental Regulatory Guide for Radiological Effluent Monitoring and Environmental Surveillance,* describes the elements of an acceptable effluent monitoring and environmental surveillance program for DOE sites possessing radioactive materials. These elements are applicable to all DOE and contractor activities for which the DOE exercises environmental, safety, and health responsibilities and are intended to be applicable over the broad range of DOE facilities and sites.

The primary purpose of this regulatory guide is to specify the necessary elements for effluent monitoring and environmental surveillance of radioactive materials at DOE sites in order to comply with both applicable Federal regulations and DOE policy. The high-priority radiological effluent monitoring and environmental surveillance program elements contained in this document are given in the form of generic performance criteria (e.g., the numeric limits and actions required for maintaining and operating an acceptable radiation protection program for the public and the environment). It also contains guidance to help define how the performance criteria can be met and includes specific actions, equipment selections, and operational methods that would be expected to meet the performance requirements.

Liquid and airborne effluent monitoring is specifically addressed in Chapters 2 and 3, respectively. These chapters provide guidance regarding these particular process monitors.

Radiation monitoring systems consist of several different types. Included in this category are CAMs, ARMs, portable and fixed-location personnel monitors, process monitors, and criticality monitors.

Continuous Air Monitors (CAMs)

10 CFR 835.403(a)(1) requires air sampling in the workplace when, under typical conditions, an individual would be likely to receive an annual intake of two percent or more of the specified annual limit on intake (ALI) values. The two percent value equates to an annual dose equivalent of 100 mrem. To assist in satisfying this requirement, CAMs are routinely used at DOE facilities.

The overriding purpose for using CAMs is to detect the presence of airborne radioactivity. These devices are designed to continuously sample and measure the air for radioactivity. They provide real-time monitoring capability. Under 10 CFR 835.403(a)(2), real-time air monitoring must be performed in normally occupied areas for one or both of the following situations: (1) where an individual is likely to be exposed to a concentration of airborne radioactivity exceeding one derived air concentration (DAC) for the radionuclide of interest or, (2) where there is a need to alert potentially exposed individuals to unexpected increases in airborne radioactivity levels.

At DOE facilities, the emphasis in the occupational setting is often devoted to detecting the presence of alpha-emitting transuranics such as plutonium, americium, etc. Beta CAMs are also used. If a preset exposure level is exceeded, possibly due to an unplanned release, modern CAMs are designed to activate an alarm system with the intent of reducing occupational exposures. CAMs should be designed to respond in the shortest possible time and at the lowest detectable level of radioactivity, keeping in mind the need to reduce, and preferably avoid, spurious alarms. Alarm capability and adequate sensitivity are requirements mandated in 10 CFR 835.403(a)(3).

Issues related to the use of CAMs include, but are not limited to:

- Design features
- Appropriate placement locations
- Choice of filter media
- Particle size dependence
- Flow rate measurements
- The ever-present problem of dealing with the presence of naturally occurring airborne radioactivity

<u>General Principle of Operation</u>

CAMs basically function by employing a flow system to steadily draw air, containing radioactive particulates, gases, or vapors, into the monitor. Particulates are deposited on some sort of collection substrate. For alpha radioactivity measurements, solid state detectors (typically a surface barrier or diffused junction semiconductor) work in concert with a multichannel analyzer (MCA) to detect, record, identify the radionuclide(s) of interest, and analyze the energy distribution. Zinc sulfide (ZnS) scintillators are also used, but for detection purposes only.

Beta particulate CAMs primarily employ gas proportional counters and/or silicon surface barrier detectors to record radiation events. Air monitors utilizing beta (plastic) scintillators, G-M detectors, and ionization chambers are being phased out, principally because of problems associated with radon progeny rejection. Those monitors employing G-M detectors tend to be larger and heavier than other CAMs because of the shielding materials required to reduce the background radiation levels.

Radioactive gases and vapors containing beta emitters are primarily collected using proportional counters and beta scintillators. Ionization chambers have also been used, but only for tritium, a radioactive gas. The larger the chamber, the more sensitive the measurement becomes.

Most CAMs separate airborne particulates through the filtration process where a physical barrier (a filter) removes particulates from the air stream. To a lesser extent, the process of inertial impaction--the removal of particulates that, due to their inertia, cannot make a bend in the air stream and are therefore impacted--is used in some CAM designs. A diagram of an impactor system used at one DOE facility is illustrated at the end of this competency. Inertial impactors either deposit the particulates on a detector or on a collection substrate placed over the detector.

Types of CAMS

There are a variety of CAMs in use today. These include particulate CAMs, ionization chamber flow-through CAMs, impactor alpha CAMs, tritium CAMs, silicon-diffused alpha CAMs, and CAMs that utilize remote monitors. Silicon-diffused CAMs are more rugged than surface barrier detectors that can be attacked chemically, for example, by hydrofluoric acid (HF), which is used at certain DOE uranium facilities during the enrichment process. Remote monitors offer the advantage of becoming part of a local area network, utilizing cable lines, telephone systems, or radio modems (telemetry) to transmit information back to a central processing unit. Modern CAMs are now microprocessor-based systems, which greatly adds to their flexibility in the occupational setting.

Design Features

Design features will vary depending on the type of CAM being used and the manufacturer of the device. A few illustrations of different CAM designs can be found at the end of this competency. Several representative design features for an alpha particulate CAM (common at DOE facilities, as noted previously) include:

- Solid state detector
- Readout display
- Multichannel analyzer
- Microcomputer technology
- Mass air flow measuring system
- Communication ports

- Calibration and alarm setting keypad inputs
- Audible and visual alarms
- Failure warning alarms
- Local/remote air intake locations
- Real time clock
- Battery backup
- Subtraction function
- Miscellaneous: size, weight, temperature range, power requirements

Several general comments related to the above design features can be made. The detector is a semiconductor with a typical diameter and active area on the order of 25 mm and 490 mm^2, respectively. A variety of filter media are used including millipore, fluoropore, cellulose, and glass fibers. Air is typically drawn into the gap between the detector and the filter. The filter and the detector are parallel to each other and separated by a distance of 5 to 7 mm. The readout display can supply a great deal of information such as time and date, flow rate, energy spectra, and measured values of count rate in counts per minute (cpm) and air concentrations (µCi/ml, Bq/m^3, etc.). Count rates on the order of one million cpm are possible. Some CAMs are equipped with strip chart recorders in selectable time units (e.g., seconds, hours). The MCA is equipped with 256 or more channels to allow measurements of specific alpha energies. The MCA has the capability of handling millions of counts per channel. Microcomputer technology has the inherent advantage of measurement and data storage capabilities. Historical files can be maintained on energy regions, volumes of air sampled, count and count rate determinations, and air concentrations. The air flow measuring system incorporates a mass flow determination that can be automatically included in air concentration calculations. Computer ports allow links between the CAM and other terminals/computers. A group of air monitors can be "networked" to a central computer. Output results can be printed for hard copy archiving. The local keypad requires a security access code, preventing inadvertent changes in operational settings. Alarms of an audible and visible nature are designed to actuate when alarm set points have been exceeded. Increases in the count rate, beyond what is expected or possibly statistical in nature, can trigger a high alarm. Failures related to the detector signal, loss of air flow, or the real time clock can result in a failure alarm. The subtraction function serves to minimize interferences from the naturally occurring radon and thoron progeny--a major point of interest when dealing with alpha CAMs. The success/failure of background subtraction techniques will influence the sensitivity of the air monitor. A sensitivity as low as four derived air concentration-hours (DAC-hrs) for plutonium-239 (Pu-239) with a typical radon-thoron background has been reported by equipment manufacturers.

DOE CAM Requirements/Recommendations

Requirements established by DOE under 10 CFR 835 regarding CAMs have been discussed previously. In addition, The DOE *Radiological Control Manual,* Chapter 5, contains several recommendations regarding their use (and that of other air monitoring devices). Article 551, in the DOE *Radiological Control Manual*, notes that radiological monitoring of airborne radioactivity should be conducted to characterize workplace conditions; to verify the effectiveness of physical design features, engineering controls, and administrative controls; and to identify areas requiring postings. In addition, Article 555 offers additional recommendations including:

- Air monitoring equipment should be used in situations where airborne radioactivity levels can fluctuate and early detection of airborne radioactivity could prevent or minimize inhalation of radioactivity by personnel. Selection of air monitoring equipment should be based on the specific job being monitored. Air monitoring equipment includes portable and fixed air sampling equipment and CAMs.
- CAM equipment should be installed in occupied areas where a person without respiratory protection is likely to be exposed to a concentration of radioactivity in air exceeding 1 DAC or where there is a need to alert potentially exposed workers to unexpected increases in the airborne radioactivity levels.

  NOTE: 10 CFR 835 does not mention "...without respiratory protection..."
- Air sampling equipment should be positioned, where possible, to measure air concentrations to which persons are exposed. Alternative methods must be used when this cannot be accomplished.
- Air monitoring equipment shall be routinely calibrated and maintained at least once per year. CAMs should be capable of measuring one DAC when averaged over 8 hours (8 DAC-hrs) under laboratory conditions.

  NOTE: The statement concerning the 8 DAC-hrs requirement does not appear in 10 CFR 835.
- CAM equipment required by Article 555.3 should have alarm capability and sufficient sensitivity to alert personnel that immediate action is necessary in order to minimize or terminate inhalation exposures.
- The proper operation of CAM equipment should be verified daily by performing an operational check. Operational checks should include positive air-flow indication, non-zero response to background activity, and internal check sources or 60 Hz electronic checks when available. CAM equipment operation should be verified weekly by checking for instrument response with a check source or with ambient levels of radon and thoron daughters.

CAM Location/Placement

In general, CAMs should be located where radioactive materials are stored in order to warn occupational workers of elevated airborne levels of radioactivity that could/do exceed administrative or regulatory limits. From a practical standpoint, proper placement requires a detailed, working knowledge of ventilation patterns and operating experience.

The issue of proper CAM placement is a serious one. In August 1993, DOE conducted a review of five contractor sites to evaluate concerns raised relative to alpha CAM performance. A team of experts examined airborne contamination data and alarm logs and determined that the CAMs alarmed only 15 to 30% of the time when an elevated airborne contamination level existed. The highest alarming percentage was disappointing, considering a room air contamination level of several hundred DAC-hrs was present. Inadequate placement of the CAM was considered the probable cause of these results. Alarm capability improved when air concentrations exhibited little variability across the room, (i.e., when the distribution of air was uniform). In contrast, when localized spills occurred, even at activity levels mentioned above, the alarm rate worsened. The team also concluded that existing methodologies for determining the proper placement of a CAM were inadequate.

In addition, the issue of the validity of conventional methods for assessing the movement of particulates in an airstream, such as a smoke test, was raised. Certain contaminants, such as plutonium, have particle sizes that do not compare favorably with that of smoke particulates. Using commonly performed airflow studies to determine the proper placement of a CAM may be simply inappropriate. The Inhalation Toxicology Research Institute (ITRI) has experimented with a generator that produces a wax aerosol containing a fluorescent dye. The aerosol has aerodynamic properties similar to alpha particles; the dye allows visual observation of the airflow patterns. Similar research in Oak Ridge, TN, has focused on titanium dioxide. However, DOE has reservations, as to whether these studies will be beneficial from a practical point of view.

A CAM should preferably be placed in close proximity to a job location where the potential for airborne contamination is high. However, because of their size and expense, CAMs often end up located near room air exhaust points; the air sampled here cannot in most cases be considered representative of a worker's breathing zone. In fact, studies have shown that there can be a wide variability in air sampling results obtained from CAMs and samplers located much closer to the worker. With that in mind, remote monitors could be used to minimize worker distraction. For example, the latest generation of CAMs contain microprocessor chips attached to the sampling head/device. Each chip has its own individual address and information from that particular sampling unit is sent back to a central processing unit. Software-driven programs, already in existence today, allow for up to 250 remote locations. Some of these locations could include the workers' breathing zone.

At DOE facilities, the presence of transuranic materials (notably plutonium) is a concern due to inhalation hazards. As noted previously, continuous real-time monitoring is required when an individual could be exposed to airborne radioactivity concentrations exceeding the DAC for the radionuclide of interest. The CAM must be equipped with alarms and sufficient sensitivity to quickly alert potentially exposed occupational workers that action is required to reduce or end an inhalation exposure.

The discussion above emphasizes that key parameters in CAM placement are the ability to:
(1) collect a representative sample--a sample representative of what the workers are breathing, and
(2) warn individuals of high air concentrations. Other noble objectives include determining when airborne radioactivity areas exist and whether confinement or leakage of radioactivity has occurred. NUREG-1400 and NRC Regulatory Guide 8.25, both titled *Air Sampling in the Workplace* discuss these issues and offer realistic airflow pattern scenarios with the aim of having the reader develop an awareness of how proper CAM locations are determined.

CAM Limitations

CAMs are not perfect devices. Some of their limitations include the following:

- The response of the instrument may not be directly related to the level of contamination in the workplace. When this occurs, the problem may lie in the placement of the monitor as discussed above.
- CAMs seldom alarm for small low-level spills, probably because of a lack of sensitivity and improper CAM placement. Though these findings are not a surprise, small spills are fairly common and could be a major source of collective dose to workers.

  NOTE: A "small" spill, according to a DOE audit team that has evaluated several DOE contractor facilities, has the potential to result in a 0.1 to 0.5 rem committed effective dose equivalent (CEDE).
- "Puff-type" releases, which are localized and settle out quickly, are not detected until 90% of the worker's inhalation uptake has occurred, according to recent DOE findings.
- CAMs are not meant to be used to quantify routine doses. Other detection mechanisms, such as surveys, personnel monitoring, and the use of area contamination monitors, are used instead.
- CAMs are rarely located in the worker's breathing zone.
- CAMs are often unavailable for use. Common problems encountered include units that are unplugged, lack of air flow, microswitch failures, and detector failures.

Selection of Filter Media

CAMs employ a variety of filters. The filter is essentially a mechanical barrier that is designed to remove particulates of varying sizes out of the airstream. The decision to use a fibrous (e.g., cellulose or glass fiber), membrane filter (millipore), or combination membrane/fibrous filter (e.g., fluoropore), requires some study. Membrane filters are often referred to as surface loading filters because airborne particulates are collected on the surface of the filter. Fibrous filters, known as depth filters, trap particulates deeper within the matrix of the filter. This can be very important from a practical standpoint; if collection of alpha radioactivity is of interest, choosing a fibrous filter could promote significant self-absorption. Knowledge of that likelihood might necessitate the use of correction factors. The reader may wish to consult the ITRI for information related to filter media characteristics.

Alpha Spectra Considerations

The nature of alpha particle interactions with matter necessitates a consideration of various factors that could degrade an alpha spectrum. Degradation results in a larger full-width at half-maximum (FWHM), resulting in poorer resolution. This effect can be caused by increased dust loading on the filter, the source-to-detector distance, and the size of the source and the detector. The air gap between the source and the detector is typically on the order of 5 to 7 mm. A gap is required to allow particulates to enter and deposit on the filter. Increasing the gap leads to alpha energy attenuation and a subsequent increase in the FWHM. It also reduces the efficiency of the detector. Reducing the source-to-detector distance also has disadvantages, notably the loss of particulates on internal walls of the sampler located in the vicinity of the detector and filter, and nonuniformity of filter collection.

As far as relative sizes of the filter and the detector are concerned, a larger filter is advantageous in that it provides a reduced pressure drop with a concomitant increase in flow rate. An increased flow rate effectively results in the collection of a greater sample without the disadvantages of filter loading and self-absorption. However, a filter that is larger than the detector results in a reduced detector efficiency because the diameter of the filter extends beyond the diameter of the detector. A larger detector with an equivalent diameter to the filter could, of course, be purchased. Cost considerations (especially when dealing with a semiconductor) would then come into play, but could be offset by increased CAM sensitivity. In short, it is not only desirable to use a comparably sized filter and detector, but to make each as large as practical, considering the factors just described.

NOTE: Worthwhile data can also be obtained if the detector is larger than the filter, but not the other way around!

Uniformity/Nonuniformity of Filter Deposits

It is preferable to collect uniform deposits of airborne particulates on a filter. Failure to do so may lead to one of two scenarios: (1) an underestimation of the particle size concentration based on efficiency considerations discussed previously, or (2) an overestimation of the concentration if the particulates end up primarily located at the center of the filter.

Particle Size Influences

The reliable operation of a CAM is strongly influenced by the variety of particle sizes collected from the airstream. For example, CAMs that operate on the principle of inertial impaction fail when collecting particles of 0.5 µm or below in size. This is considered significant in certain situations. Larger particles have also been observed to rebound off the collection surface of these particular devices and/or cause the dislodging of particles previously collected. In the latter instance, greasing the collection substrate (typically a planchet) will minimize this effect, but correspondingly degrade the energy spectrum. In other types of CAMs, larger particulates may end up lost on internal walls of the sampler, creating a bias toward the collection of smaller particulates on the filter media.

McFarland et al., *Health Physics*, Vol. 62, have discussed the idea of establishing a performance criterion of 10 µm as the "cut point" for present-day CAMs. This consideration developed a few years ago when the Environmental Protection Agency (EPA) established that 50% of the particles of this size penetrate to the tracheobronchial (T-B) region of the lung.

System Reliability

There are several characteristics that a reliable air monitoring system should possess. A fundamental trait of the system is that it provide consistent responses to levels of airborne radioactivity. The precision (reproducibility) of the measurement can often be of greater importance than the accuracy of the measurement. A case in point is the measurement of airborne plutonium in the workplace. Respect and subsequent reliance of workers on these air monitors develops only after these systems demonstrate that the number of spurious alarms are minimized and that they will actuate an alarm after detecting (in a consistent manner) the lower limit of detection (LLD) for the radionuclide of interest. Secondly, the reliability of a CAM will be tested due to everyday usage. It may have to tolerate a wide range of environmentally harsh conditions. Even under these conditions, it is desirable that CAMs remain relatively problem free for as long as possible (e.g., a few years). Lastly, adherence to a strong maintenance and calibration program is an absolute must to achieve the desired performance of the system over the long term.

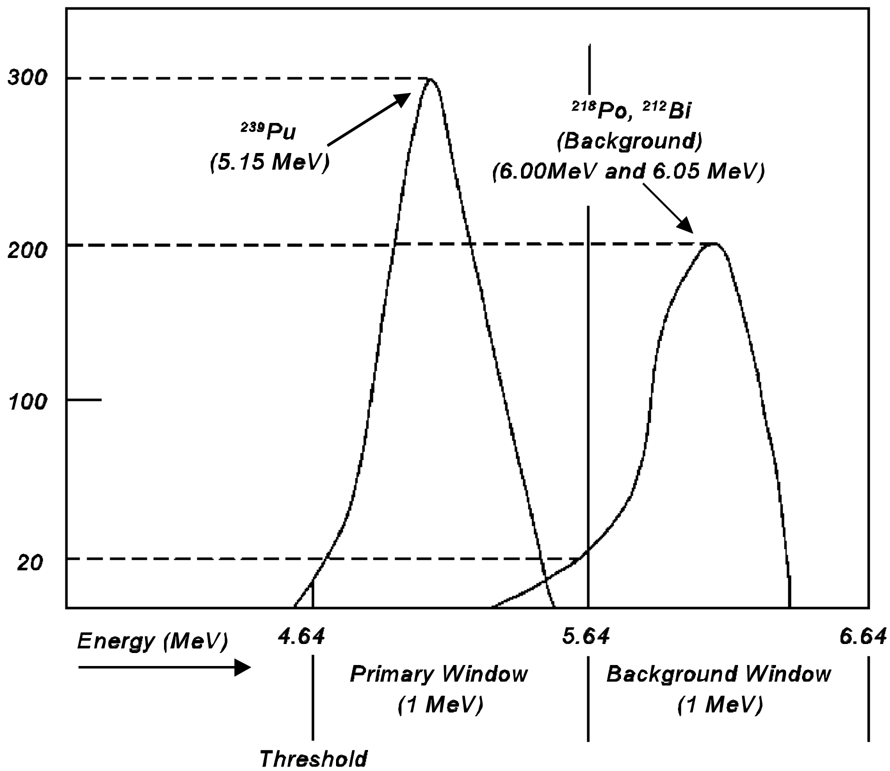
Discrimination Against Natural Airborne Radioactivity

One issue of concern in both the design and operational end of a CAM system is the presence of natural airborne radioactivity, principally composed of radon and thoron progeny. These radionuclides can contribute significantly to the background on a CAM system because they emit alpha and beta radiations--the same radiations looked for in the occupational setting. As noted earlier, the DOE *Radiological Control Manual* recommends that CAMs be capable of measuring one DAC when averaged over eight hours under controlled laboratory conditions. Recall that this requirement was dropped altogether in 10 CFR 835.

At the Waste Isolation Pilot Project (WIPP) facility near Carlsbad, NM, background aerosols are produced from surface dust, which has been filtered through the ventilation system, produced during mining operations, or exhausted from vehicle emissions. Salt dust, also containing background radon/thoron progeny, is produced, primarily through mining operations. These dusts load on the collection media, degrade the alpha spectra, and reduce the number of counts due to man-made radioactivity, while the background count rate tends to rise. The likelihood of a false alarm is increased. The dusty environment of the WIPP facility offers real challenges for those CAM instruments employing alpha spectroscopy.

The difficulty in discriminating natural radioactivity from that generated in the workplace occurs because the energies associated with alpha decay from radon and thoron daughter products are very similar to alpha energies generated by man-made processes. For example, one of the radon progeny, polonium-218 (Po-218), emits a 6.0 MeV alpha particle. Bismuth-212 (Bi-212), found in the thorium series, also decays by alpha emission with an energy of 6.05 MeV. Once self-absorption in the filter media and attenuation of energy caused by the air gap between the filter and the detector is taken into account, these alpha energies can overlap with other radionuclides of interest, most notably the radionuclides plutonium-239 (Pu-239 [5.15 MeV]), plutonium-238 (Pu-238 [5.50 MeV]), and americium-241 (Am-241 [5.49 MeV]).

Several different methods have been used to provide solutions to this problem. A common approach is to use a background compensation technique employing a numerical algorithm to subtract background counts from the energy region of interest. If the algorithm is successful, the sensitivity on the low end will be improved and consequently, the alarm rate will be reduced. Secondly, inertial impaction devices are used to remove the source of background interference by collecting the heavier man-made alpha emitters on a planchet by impaction while exhausting the much smaller sized radon/thoron progeny from the CAM. The planchet is also often removed periodically and counted after a sufficient period of time has passed to allow for decay of the shorter-lived materials; this type of information is useful in developing a historical database for the long-lived contaminant of interest. A third solution to this problem usually entails setting an "energy window," an electronic setting in the instrument, to minimize background influences. This approach is illustrated in the following figure. A single-channel analyzer can be employed to first measure the Po-218 and Bi-212 levels and then electronically subtract them out from the rest of the spectrum. More recently, McFarland et al., *Health Physics*, Vol. 62, have experimented with a screen-type preseparator to remove radon/thoron daughters. The authors reported a removal efficiency of 99%. Each of these methods has its limitations, but is intended to improve the CAMs detection sensitivity and reduce the possibility of an inadvertent alarm to an acceptable level.



CAM Maintenance, Surveillance, and Calibration

Proper calibration and maintenance is essential to the continued reliability of an air monitoring system. To that end, maintenance and calibration programs must be developed. Proper maintenance and calibration of air monitors must be performed in accordance with applicable standards and regulations. ANSI N323-1978, *Radiation Protection Instrumentation Test and Calibration*, requires periodic performance testing and calibration. New equipment should be inspected and undergo acceptance testing upon receipt. A record of each instrument's maintenance history should be developed as a way to track system performance. Radiation check sources should be calibrated monthly. Calibration of the CAM should be performed using a documented procedure and qualified individuals. At DOE facilities, calibrations are typically performed on an annual basis. Quarterly calibration schedules are also used at some DOE facilities. In practice, there are significant differences in the complexity of calibration procedures at these facilities; procedures for the calibration of CAMs range from quite detailed (a variety of internal components are checked) to simple (signal-in, signal-out tests). The CAM air-flow measuring device, usually a simple rotameter, should be recalibrated at least annually.

CAM surveillance and testing includes items such as changing filter paper, conducting performance testing, visually inspecting the unit, calibration, and maintenance. Time frames for conducting these tasks can be as frequent as once each shift (for routine visual inspections) to as much as one year (calibration/maintenance procedures). Each facility determines how often these activities will be performed.

Airborne Radioactivity Samplers

Purpose

Air sampling is performed to determine the cleanliness of the air environment in the work area or in the air exhausted to the outside environment, as in the case of stack sampling. It is also done to check the effectiveness of laboratory design and/or work procedures as applied to contamination control. Air sampling equipment should be positioned to measure air concentrations to which persons are exposed. If this cannot be achieved, a program of personal breathing-zone air sampling should be initiated. The objectives of air sampling are to:

- Measure the concentration of the contaminant in the air (detection and analysis)
- Identify the type and characteristics of the contaminant, to help evaluate the hazard potential
- Appraise the performance of control equipment or procedures

A common practice is to use allowable concentration values as an index of the degree of control achieved. Then, measured concentrations well below the allowable limit imply satisfactory control. To document that control is being maintained, a routine air sampling program must be carried out.

Principles of Detection and Operation and Field Application(s)

Factors which need to be considered in setting up an air sampling program are frequency of sampling, collection time, sampler type, and volume flow rate. The choices that one has will often be influenced by the form, nature, and containment of the radionuclide being sampled, as well as, the type of operation being performed. In general, for a given radionuclide, one should sample a large enough volume so that 1/10 of the allowable concentration can be measured. However, the method of analysis with respect to its sensitivity and accuracy will affect the sample volume needed.

Basically, two types of samples are collected. A volume or grab sample is one in which part of the universe, with the contaminant in its original concentration, is isolated. This sample gives conditions at a point in time and space. Many such samples may be needed to adequately describe average conditions in a large area. A continuous or integrated sample is one in which the contaminant is accumulated in the collecting medium during the entire period of interest. This sample gives an average concentration during the collection time and does not reveal any "fine structure" in the air concentration. Samples of either type may be taken for both gases and particulates.

Filter Samplers

The filter sampling technique is to draw air at a known flow rate through a filter for a known length of time. A filter sampler is the most common device used for sampling radioactive particulates. A wide choice of filters is available and there is one suitable for almost any purpose. Among the characteristics that influence a choice of filter are collection efficiency, flow resistance, and mechanical strength. No one filter excels in all of these characteristics, so a compromise is required.

Analysis is commonly done on filter paper samples by gross counting of alpha and beta activities. This may be accomplished in stacked proportional counters (piggyback probes). Solid-state detectors and/or plastic scintillators, such as Pilot B (diphenyl stilbene in clear plastic), have also been employed to count these samples. Semi-automatic, microprocessor (minicomputer) based systems have been used at facilities with a large number of routine samples to analyze. For alpha counting, the self-absorption in the paper must be taken into account.

Once the sample is collected, the activity on the filter can be determined in several ways. Gross alpha or beta counts can be taken and from these the filter activity can be calculated using a previously determined counter efficiency. Spectroscopy analysis can also be performed for specific energies of a suspected contaminant.

Grab Samplers

A grab sampler is a partially evacuated container that can be used to sample for airborne gases or particulates. The container could be connected to a vacuum pump, evacuated, isolated, and then removed to the sampling location. There it is opened, admitting the atmosphere to be sampled, then isolated once more, and removed for analysis.

For analysis, the G-M tube is connected to a scaler and a gross count is made. This count can be converted to activity in the sampler volume, if the system has previously been calibrated with a known activity of the isotope of interest. Such a calibration must be made since the counting efficiency of the detector depends strongly upon the energy of the emitted radiation.

The weakness of this method is its low efficiency. A 3.5 liter sampler, using a0.3 kg/m^2 tube 76 mm long, has an efficiency of about one percent Ar^{-41}. To ensure a more representative concentration, one should take a number of grab samples and average the results. Longer pressurized samplers, obtaining more volume, are available. Grab samples may also be taken in glass bulbs or bottles and are analyzed using pulse-height analysis. This has the added advantage that one is able to identify the radionuclide. With the proper setup, the system may be calibrated to determine the activity concentration.

Impingers and Impactors

In the impinger, particles are removed by inertial precipitation from a sharply deflected airstream. After impinging against a surface at right angles, the airstream continues. Because of their inertia, particles above a certain effective size cannot follow and are collected on the deflecting surface which has been greased to enhance retention.

The cascade impactor consists of several impingement states, in series, followed by a final filter. Particle sizes are selected by reducing the size and impingement distance of each succeeding orifice, thereby increasing flow velocity and causing smaller particles to be deflected from the airstream. A crude particle-size spectrum is obtainable this way. However, distortion may be introduced because of the breakup of the larger agglomerates undergoing impingement and retention failure (particles bounding from an upper stage to a lower stage). This is a problem with all impingement devices. If collection was ideal, then the particles collected on any stage would have diameters between two fixed values. Overlap in sizes does occur, so each stage must be calibrated. Impactors have been found useful for sampling in the presence of natural radon daughter activity, which is usually associated with particles smaller than 0.3 µm in diameter.

Condensation Devices

A cold trap immersed in a bath of dry ice and alcohol, liquid nitrogen, or other suitable coolant can be used for sampling nonreactive or insoluble gases. Dry ice and alcohol are used as a coolant to freeze out tritated water vapor. A dehumidifier may also be used. A liquid scintillation count of the collected water gives the tritiated water vapor activity per unit mass of water vapor. Relative humidity and temperature measurements, made at sampling time with a psychrometer, give the concentration of water vapor per unit volume of air, when corrected for the barometric pressure. The product of these two numbers give the tritiated water concentration per unit volume of air at the sampling time.

The condensation method is not usedd extensively for other gases, since the water vapor in the air hinders the collection process. Often, it is necessary to remove the water for efficient collection.

<u>Adsorbers</u>

Adsorbers such as activated charcoal, silica gel, or metal gauzes (silver (Ag), copper (Cu) are used for collecting organic vapors and nonreactive gases and vapors such as xenon, krypton, and argon. The technique involves bringing the sampled atmosphere into intimate contact with a finely divided or porous adsorber. The efficiency of collection is generally enhanced by maintaining the adsorber at a reduced temperature.

Area Radiation Monitors (ARMs)

ARMs are utilized to control radiation exposures in a workplace setting. A variety of ARM systems exist to detect gamma and neutron radiation. Emphasis is typically placed on the detection of gamma radiation intensities throughout the facility. To satisfy that objective, ARMs are either wall-mounted or operated as a freestanding unit in areas requiring monitoring. These devices tend to be fairly rugged and versatile, yet compact and lightweight. G-M or ionization chamber detectors are typically used. Depending on the detector, energy compensation is provided to allow a flat roentgen response versus gamma energy. Radiation levels ranging from 0.01 mR/hr up to 10,000 R/hr are typical. ARMs are designed to provide normal/fail indicators for safe operation; remote indicators are available that include meter, audible, and visual alarms. High radiation alarms and alarms designed to "alert" the worker that an alert level has been exceeded can be set over the entire meter range. Audible alarms often consist of a horn; visual alarms employ a light or beacon, which may flash on and off depending on the design.

ARMs for slow neutron detection can use proportional counters by taking advantage of any number of charged particle reactions including: baron-10 (B-10) [n, alpha] reaction, helium-3 (He-3) [n,p] reaction, and lithium-6 (Li-6) [n, alpha] reaction. Because charged particles are generated in these reactions, scintillation materials such as zinc sulfide (ZnS) can be used to detect neutrons. Other means of slow neutron detection are fission chambers, which contain fissile material that interacts with thermal neutrons causing fission. The neutron flux is measured by the intensity of the gamma radiation given off during fission.

Fast neutron detection usually incorporates a moderator such as paraffin to thermalize fast neutrons to induce a slow neutron reaction discussed above. Fast neutrons can be detected by using scintillation materials with a high hydrogen content to produce a proton. Scintillation materials containing hydrogen include anthracene, or stilbene.

From a regulatory perspective, the use of stationary (area) or portable radiation instrumentation for the purpose of measuring ambient radiation dose rates is required under 10 CFR 835.403(b). The DOE *Radiological Control Manual* (Article 553) recommends that:

- ARMs should be:
  - Installed in frequently occupied areas where the potential exists for unanticipated increases in dose rates.
  - Also placed in remote locations where a need for local indication of dose rates prior to personnel entry exists.
  - Used to measure only the radiation for which the calibration is valid.
  - Tested at least quarterly to verify audible alarm system operability and audibility under ambient working conditions and operability of visual alarms, when so equipped.
- The need and placement of an ARM should be documented and assessed when changes to facilities, systems, or equipment occur.
- Where an ARM is incorporated into a safety interlock system, the circuitry should be such that a failure of the monitor should either prevent entry into the area or prevent operation of the radiation-producing device.
- ARMs should not be substituted for radiation exposure surveys in characterizing a workplace.
- If installed instrumentation is removed from service for maintenance or calibration, a radiation monitoring program providing at least equal detection capability should be maintained, consistent with the potential for unexpected increases in radiation dose rates.

Criticality Detection/Alarm Systems

The purpose of nuclear criticality accident alarms and alarm systems is to alert personnel to promptly evacuate the area to reduce the risk of exposure to radiation. Generally, the nuclear criticality accident alarm system is meant to prevent large exposures to many people.

A nuclear criticality accident occurs without advance warning. There are no discernible indications that the accident is about to happen. Therefore, nuclear criticality accident alarm systems are "after-the-fact" alarms. Generally, the alarm will sound about a half a second after the criticality has occurred.

ANSI/ANS-8.3-1986, *Criticality Accident Alarm System*, addresses not only the need for alarm systems, but also describes the characteristics of alarm signals, dependability, testing procedures, and emergency planning. The specifications for alarm signals include recommended sound pressure levels and activation mechanisms that do not depend on human action.

The standard also provides guidance on the criteria for system design including:

- Reliability
- Vulnerability
- Seismic Tolerance
- Failure Warning
- Response Time
- Detection Criterion
- Sensitivity
- Spacing

Criticality alarm systems are generally composed of neutron or gamma radiation detectors and annunciation (signal) equipment. In addition, administrative procedures are needed to ensure that the equipment is maintained and properly calibrated.

As stated in ANSI/ANS-8.3, "Criticality alarm systems shall be designed to detect immediately the minimum accident of concern. For this purpose, in areas where material is handled or processes with only nominal shielding, the minimum accident of concern may be assumed to deliver the equivalent of an absorbed dose in free air of 20 rad at a distance of 2 meters from the reacting material within 60 seconds." Therefore, the minimum accident of concern assumption determines the alarm set point and the detector spacing in a work area.

The selection of the detector will generally be determined by the fissile material being used and the type of radiation emitted in the event of a criticality accident. Some facilities can accidentally produce gamma fluxes capable of setting off a criticality alarm without actually having a criticality. This situation would produce false alarms; therefore, a neutron detector would more likely be used instead of a gamma detector.

Li-6 used in combination with other elements is an example of a neutron detector. G-M detectors and NaI detectors could be used to detect gamma radiation.

The basic principle of operation is described in the following example.

Detector Type: Zinc sulfide/lithium-6 (ZnS /Li-6) doped neutron scintillator

- A polyethylene moderator is used to enhance neutron capture.
- Neutron capture by Li-6 produces α particles.
- The reaction of ZnS and α produces visible light photons.
- Light pulses are detected by a photomultiplier tube (PMT), producing electric signals proportional to the neutron flux.

Criticality accident alarms and alarm systems generally have built-in signals that indicate a malfunction or loss of power. These signals may be visible, audible, or both. Some alarms have built-in battery backup systems with battery chargers.

The alarms and alarm systems are tested periodically to ensure that:

- The system is operating within the design specifications, especially following modification or repair, including maintenance of redundancy.
- The system responds to radiation as designed.
- The evacuation signal is audible above background noise. This signal must be discernible as an evacuation alarm.
- Test results are recorded and maintained for each system.

Personnel Contamination Monitors

Personnel monitors are designed to determine the amount of radioactivity that might be present on personnel--in their excretions, on their skin, or any part of their clothing. 10 CFR 835, Subpart E, requires workplace monitoring. Section 835.401 lists the general requirements for workplace instrumentation including:

- The need for periodic maintenance and calibration
- The choice of appropriate instrumentation for the type(s), levels, and energies encountered
- Consideration of environmental conditions to which the instrument(s) would be exposed
- Determination/confirmation of the operability of the instrument

Section 835.404 addresses more specifically the requirements for radioactive contamination control and monitoring. The instrumentation selected must be able to satisfy the requirements of 10 CFR 835.

While the use of portable instrumentation is an important component of contamination control, this section emphasizes the use of fixed (stationary) personnel contamination monitors. These devices are typically designed to allow the user to place his/her hands and feet in the monitor ("hand and foot" monitors), wait for a sufficient period of time to achieve sufficient sensitivity, and then inform the individual as to whether he/she is free of contamination. Visual and audible alarms are utilized to relay the contamination status to the individual. These monitors are meant to signal the presence of radioactivity, not necessarily the exact location. If contamination is found, portable radiological instrumentation can localize the area of contamination and facilitate decontamination procedures. Large area detectors are in use that allow the detection of contamination over a much larger area of the body.

Fixed personnel monitors primarily employ gas-flow proportional counters and fixed-volume (gas-filled) G-M detectors to detect alpha, beta, and gamma radiation. Thin mylar windows are required to allow detection capability, especially in the case of alpha particles. In some cases, solid-filled scintillation detectors are used for detection of alpha radiation.

These monitors should be placed at strategic locations in the facility. Common locations include egress points from radiologically controlled areas where contamination could potentially exist. The number of monitors is influenced by the number of work stations and the locations where higher contamination levels are found.

Process Radiation Monitors

Process radiation monitors are designed to detect concentrations of liquid and gaseous radioactivity in work areas, stacks, ducts, laboratories, etc. A variety of these systems exist and are routinely used as indicators of both normal and abnormal system operating conditions. They may also provide an estimate of the quantity of radioactivity released to the environment.

> DOE EH/0173T, *Environmental Regulatory Guide*, addresses liquid and gaseous effluent monitoring in Chapters 2 and 3, respectively. Both chapters are intended to assist each DOE-controlled facility meet the requirements of DOE Order 5400.1, *General Environmental Protection Program Requirements*, and DOE Order 5400.5, *Radiation Protection of the Public and the Environment*.

Chapter 2 discusses general criteria and monitoring requirements, performance standards for liquid effluent monitoring systems, sampling and monitoring systems design criteria and considerations, alarm levels, and quality assurance.

Monitoring of liquid wastes should be performed to:

- Demonstrate compliance with DOE Order 5400.5 (specifically Chapter 2)
- Quantify radionuclides released from each discharge point
- Alert appropriate personnel of “upsets” in processes and emissions controls

Continuous radionuclide monitoring is recommended for routine releases that could exceed one derived concentration guide (DCG) at the release point when averaged over one year or unanticipated releases exceeding one DCG averaged over one year. Continuous sampling combined with frequent analyses can substitute for continuous monitoring if emissions cannot be detected by technically current continuous monitoring devices. Appropriate statistical parameters should be considered to determine the accuracy of sampling results. The regulatory guide points out that the level of monitoring effort is determined by the importance of the sources during routine operations and the potential for accidental releases to the environment and dose to the general public.

Performance standards for a liquid effluent monitoring system are based on a careful characterization of several parameters. These include the source(s), pollutant(s), sample collection system(s), treatment system(s), and final release point(s) of the effluents.

If a facility is new or has been modified, a preoperational assessment is recommended to determine the impact on effluent release quantity, quality, and sensitivity of the monitoring or surveillance system. This assessment should be used to determine liquid effluent types and quantities, and facility monitoring needs. It is important that the system perform to a level that allows compliance with DOE Order 5400.5 (specifically, being able to detect radionuclide concentrations at or below the DCG in addition to meeting reporting requirements). Sufficient sensitivity regarding statistical detection levels is advocated.

Performance standards include consideration of continuous monitoring/sampling, sampling systems, calibration of monitoring and sampling systems, and environmental conditions.

Design criteria associated with liquid effluent systems exist to promote representative sampling. The following general criteria assist in meeting that objective:

- Location for sampling and monitoring
- Use of a highly reliable sampling pump where needed to provide uniform continuous flows
- Redundant sampling collection systems or an appropriate alternative
- Sampling ports located sufficiently downstream of the final feeder line to promote complete mixing
- Sampling a proportional amount of the full effluent flow
- Accuracies within ±10% regarding effluent streams and sample-line flows
- Emphasis on maintaining structural integrity of the effluent sampling lines

Design considerations for the liquid effluent monitoring systems include the following:

- Purpose - Monitoring provides a prompt signal if a significant release occurs. Written procedures are advocated to document the actions that should be taken if an abnormal signal is detected. Both in-line and off-line monitoring may be required to accommodate routine and emergency monitoring.
- General Design Criteria - The type of radiation influence whether actual direct measurements or sampling and analysis is required (or a combination thereof). Alpha emitters and some beta emitters pose concerns from a measurement perspective; therefore, sampling and analysis should be performed to quantify releases associated with these radiations. Gamma radiation can usually be detected by direct measurement. Shielding may be required for high background areas. In these cases, off-line monitoring is encouraged. Grab samples can be utilized for "batch" releases where the concentration of radioactivity is constant, but the release is of short duration. When "continuous" effluent streams are present, continuous monitoring and/or sampling should be performed. Environmental conditions influence the design of the monitoring/sampling system. Air conditioning and heating provide reliable system operation to minimize worker exposures; background dose rates are considerations in accessing the system for calibration and servicing. Shielding should be considered when warranted.

Alarms are recommended to provide timely warnings and signal the need for corrective actions prior to a release exceeding the limits or recommendations in Order 5400.5. The collection of a variety of samples (grab, continuous, or proportional) is encouraged to detect the levels of radioactivity before significant impacts on the public or the environment occur.

General quality assurance (QA) provisions are contained in Chapter 10 of the regulatory guide. Specific requirements should be detailed in a facility/site-specific QA plan.

Four basic sampling alternatives are noted in the regulatory guide:

- Off-Line Periodic - Grab samples of waste streams are taken on a periodic basis, concentrated (if needed), and delivered to the laboratory.
- Off-Line Sequential - Time aliquots of the effluent are taken when a relatively constant waste stream flow rate is present.
- Off-Line Proportional - Known fractions of the effluent are collected on a continuous basis prior to laboratory analysis.
- Off-Line Continuous - Samples are continuously collected at a known, uniform rate.

In the laboratory, the presence of alpha, beta, and gamma radioactivity in liquid effluents can be determined in different ways. For example, the sample can be placed in a stainless steel vessel holding approximately 20 to 25 liters of water. Various detectors are utilized to detect the radioactivity. Alpha and beta radiations, for instance, can be detected using proportional or liquid scintillation counters while gamma radiation is detected with NaI scintillators. These monitors tend to be quite heavy, often weighing on the order of 2,000 to 3,000 pounds.

Chapter 3 of the DOE *Environmental Regulatory Guide* is devoted to airborne effluent monitoring. This chapter begins by stating that airborne emissions from a DOE-controlled facility should be evaluated and assessments made of the potential for release of radioactivity.

This assessment is important in that it directly impacts the preparation of the site's effluent monitoring and environmental monitoring programs (discussed in DOE Orders 5400.1 and 5400.5, respectively).

The regulatory guide recommends that airborne emissions, having the potential for causing doses exceeding 0.1 mrem effective dose equivalent (EDE) to a member of the general public (under a realistic scenario) for emissions in a year, should be monitored. Chapter 3 describes various aspects of airborne effluent monitoring. These include general criteria and monitoring requirements, requirements for compliance with EPA regulations, performance standards for air sampling systems, design criteria for system components, point-source design criteria, alarm levels, and QA.

The following table, taken from the regulatory guide, lists the criteria for establishing an airborne emission monitoring program. The scope of the monitoring effort is dependent on the impact of the sources and the potential for accidental releases.

Criteria for Emission Monitoring	
Calculated Maximum Dose from Emissions in a Year to Members of the Public: H_E mrem (effective dose equivalent [EDE])	Minimum Emission Monitoring Criteria*
$H_E \geq 1$	1. Continuously monitor emission points that could contribute ≥0.1 mrem in a year 2. Identify radionuclides that contribute ≥10% of the dose 3. Determine accuracy of results (±% accuracy and % confidence level) 4. Conduct a confirmatory environmental survey annually or Monitor at the receptor: 1. Continuously sample air at receptor 2. Collect and measure radionuclides contributing ≥1 mrem (EDE) above background 3. Establish sampler density sufficient to estimate dose to critical receptor given typical variability of meteorological conditions 4. Obtain prior approval from EPA
$0.1 < H_E < 1$	1. Continuously monitor emission points that could contribute ≥0.1 mrem in a year 2. Identify radionuclides that contribute 10% or more of the dose 3. Conduct confirmatory effluent monitoring at emission points where possible 4. Conduct a confirmatory environmental survey every few years
$H_E < 0.1$	1. Take periodic confirmatory measurements 2. Test to determine need to monitor by calculating dose (H_E) for normal operation, assuming that the emission controls are inoperative 3. Conduct a confirmatory environmental survey at least every five years

*Alternative criteria may be obtained through EH following coordination with EPA.

DOE-controlled facilities are subject to requirements put forth by the Environmental Protection Agency (EPA). Regarding air emissions, the two main regulations of interest are:

- 40 CFR 61, *National Emission Standards for Hazardous Air Pollutants*. The specific emission standard of 10 mrem is found in Subpart H of this regulation.
- 40 CFR 192, *Health and Environmental Protection Standards for Uranium and Thorium Mill Tailings*

The frequency for conducting continuous monitoring and/or sampling is stated in the previous table. Other performance parameters track very closely with those discussed under liquid effluent monitoring. This particular section differentiates the manner in which airborne emissions can occur (i.e., "point" versus "diffuse" sources). Point sources imply a release from a single defined point (a vent or stack are typical examples). Diffuse sources cover much larger areas. Examples include ponds, contaminated areas, and structures without ventilation or with ventilation that does not have a well-defined release point. Diffuse sources, by their nature, receive significant attention in terms of their impact on public dose and the environment. The regulatory guide recommends that these sources be identified and assessed. Further, diffuse sources contributing a significant fraction of the public dose should not only be identified and assessed, but documented and verified annually.

The quantification of airborne emissions through the use of sampling and monitoring systems relies on such factors as timeliness, representative sampling, and adequate sensitivity. Characterizing and documenting sources of emissions requires consideration of several factors.

These include the identification of:

- Actual or potential radionuclides by type and concentration
- Fallout and naturally occurring radionuclides
- Materials of a biological or chemical nature that negatively impact on the goals of the sampling and monitoring program
- Internal and external conditions such as environmental conditions, factors that lead to a complete loss of the system, and gas-stream characteristics

This section of the regulatory guide offers extensive information on design criteria for "point" emission sources. Furthermore, several important references are noted to assist responsible individuals at DOE facilities with implementing these criteria. Each subsection under this topic is listed in the following table along with cited references. The reader is encouraged to consult these additional sources of information.

Point Source Design Criteria (Subsection Heading)	Reference(s)
Gas-Stream Characterization Methods (3.5.1)	EPA Methods 1,2,4; ASTM Annual Book of ASTM Standards (1985)
Location of Sample Extraction Sites (3.5.2)	EPA Method 1; ANSI N13.1-1969
Sample-Extraction Probes (3.5.3)	EPA Method 5; ANSI N13.1-1969
Sample Transport Lines (3.5.4)	EPA Method 5; ANSI N13.1-1969
Air Moving Systems (3.5.5)	Not Applicable
Air Flow Measurements (3.5.6)	DOE/EP-0096; ANSI N13.1-1969
Sample Collectors (3.5.7)	ANSI N13.1-1969
Continuous Monitoring Systems (3.5.8)	ANSI N42.18-1974 (R 1980); DOE/EP-0096; ANSI N317-1980

Several types of instrumentation are utilized at DOE facilities for the measurement of specific radionuclides. These include tritium monitors, ionization chambers (for gaseous tritium), radioiodine monitors, noble gas monitors, gross alpha and beta monitors, transuranic radionuclide monitors, uranium monitors, and particulate fission and activation product monitors. Each of these monitors have their own design features and capabilities.

Some of these process monitors are typically placed near stacks and ducts. Representative design features for these locations include:

- Self-containment
- Background subtraction
- Noble gas compensation
- Continuous readout displays
- Several alarm functions (including normal, fail, alert, and high), audible alarms (e.g., a horn), and visual alarms such as a rotating beacon
- A pump (usually self-regulated)
- Flow rate and pressure indicators

One disadvantage of these systems is their weight. Due to shielding requirements, these systems often weigh on the order of several hundred pounds. Several different detectors are used depending on the application. For example, radioiodine monitors typically employ a sodium iodide [NaI(Tl)] scintillator.

Particulate beta emitters, radioactive iodine, and noble gases can be simultaneously collected using a Particulate Iodine Noble Gas *(*PING) monitor. These self-contained, cart-mounted systems are often placed near stacks and ducts for the purpose of providing effluent monitoring. The system is designed to remove the particulate fraction through the use of a filter, the iodine component using activated charcoal (or silver zeolite) cartridges, and finally the noble gas contribution by collecting a specified volume. PING systems utilize inorganic NaI scintillators for the presence of gamma radiation and organic (plastic) scintillators or energy-compensated

G-M detectors for beta radiation. To subtract the interfering radon progeny contribution, solid-state alpha detectors can be used. As with most process monitors, they are not easily transportable.

Radiation Instrumentation Calibration

<u>Standards</u>

Two standards that exist for calibration of radiation instruments are the American National Standards Institute publication, ANSI N323-1978, *Radiation Protection Instrumentation and Calibration* and the National Council on Radiation Protection (NCRP) Report 112 , *Calibration of Survey Instruments Used in Radiation Protection for the Assessment of Ionizing Radiation Fields and Radioactive Surface Contamination*.

<u>Elements</u>

The elements of a radiation instrument calibration program should evaluate the level of calibration, instrument source check, technical considerations of source selection, instrument response considerations, uncertainty in the calibration process, frequency of calibration, and calibration records.

<u>Calibration and Source Check Frequency</u>

Source Check

In between regular calibrations, instruments should be performance checked before use. The deviations should not exceed more than +/- 20% from expected readings.

Calibration Frequency

According to 10 CFR 835.401(c)(1), instruments used for monitoring and contamination control shall be, "periodically maintained and calibrated on an established frequency of at least once per year." Additionally, ANSI N323-1978, *Radiation Protection Instrumentation Test and Calibration* suggests calibration be performed at least annually. Where instruments are subjected to extreme operational conditions, hard usage, or corrosive environments more frequent primary calibration should be scheduled. Also, if an instrument fails a source check or has undergone modification which might affect its response, it should undergo recalibration.

<u>Source Selection</u>

Some general considerations in determining radioactive sources are half-life, range of energies emitted, and physical form. Sources should have long half-lives and physical forms that enable ease of use.

Some of the technical considerations in selecting a source are the type of radiation emitted, source strength and intensity, source to detector geometry, source accuracy for field intensity determination, and incidental and spurious radiations. It is important for the calibration source to emit radiation which is representative of that expected in the field. This includes type of radiation, intensity and any interferences from mixed radiation fields.

It is recommended in NCRP 112 that radiation source intensities may need to yield absorbed dose rates or kerma (kinetic energy released in matter) rates from less than 0.1 gray (Gy) hr^{-1} to greater than 100 Gy hr^{-1}. Sources used to calibration surface contamination instruments may require activity levels anywhere from 100 becquerel (Bq) to 10 kBq.

Following are examples of radiation sources recommended in ANSI N 323-1978.

PHOTON SOURCES

Radionuclide	Decay Energy (keV)	Half-life
Am-241	60	433 years
Co-57	122	270 days
Cr-51	320	28 days
Cs-137	662	30.1 years
Ra-226	830	1,600 years
Co-60	1,250	5.27 years
Na-24	2,000	15 hours

ALPHA SOURCES

Radionuclide	Decay Energy (MeV)	Half-life
Gd-148	3.18	93 years
Th-230	4.6	7.7×10^4 years
Pu-239	5.1	2.4×10^4 years
Po-210	5.3	138 days
Am-241	5.4	433 years
Pu-238	5.4	87.8 years
Cf-252	6.0	2.65 years

BETA SOURCES

Radionuclide	**Decay Energy (E_{AVE} MeV)**	**Half-life**
H-3	0.0057	12.3 years
C-14	0.049	5,730 years
Ca-45	0.077	164 days
Tl-204	0.243	3.78 years
P-32	0.695	14.3 days
Sr-90	0.566	28.5 years
K-42	1.43	12.4 years

Other considerations include:

Traceability

Calibration sources should be traceable to the National Institute of Standards and Technology (NIST). This can be accomplished by several means, such as:

- NIST tracable sources are prelisted.
- Calibration sources are sent to NIST for calibration.
- Instruments are sent to NIST for calibration, these instruments are then used to calibrate the facility sources and/or fields.
- Sources or instruments are sent to a secondary calibration laboratory for calibration.

Energy Dependance

Gamma radiation interactions (i.e., photoelectric, compton scatter, and pair production) are all photon energy dependent. For this reason the response of gamma radiation detectors is energy dependent. Ion chambers exhibit the most energy independent response over the compton interaction range of 0.2 MeV to 2 MeV. Most gamma emitters encountered in the workplace fall within this energy range. However, most detectors exhibit the most energy dependence to lower (below 0.2 MeV) photon energies, particularly characteristic x-rays. Other instruments exhibit the most energy dependence to beta particles below 0.5 MeV and neutrons below 1 MeV. Knowledge of the magnitude of the energy dependence is essential when the same instrument may be used to assess various radiation fields from different sources.

Radiation Instrumentation Sensitivity

Background

Radiation exists in our environment from both natural and man made sources. Natural radiation includes cosmic and terrestrial sources. Man made sources of radiation include medical and consumer product sources.

All radiation instrumentation is effected by background radiation of some sort, whether it is from natural or man made sources. When counting radiation samples, corrections must be taken to account for background radiation to prevent interference with the sample count. This is accomplished by counting a blank sample for a given period of time. The value of the background is then subtracted from the sample counts to obtain a true sample count.

There are specific terms for various counts, for example, a gross sample count includes both a sample count and a background count. A net count is attributed to the sample and is calculated by subtracting the background count from the gross sample count. It is important to understand that the term net count implies that background has been subtracted and, therefore, the count is due to the radioactivity in the sample.

Minimum Detectable Activity

Radioactive decay is a random process that lends itself to statistical analysis. Because of this randomness of decay, limits or decision points must be calculated to determine whether or not activity exists in the sample or whether the counts fall within acceptable parameters for random background variations. One such statistical analysis is called minimum detectable activity (MDA).

MDA can be broadly defined as the smallest amount of activity present in a sample that may be detected by a particular instrument to a predetermined confidence level. In health physics the confidence level is generally 95%. This implies that we have 95% chance of detecting the activity and only 5% change of nondetection. There are no standard formulas to calculate MDA, but following is an example:

$$MDA = \frac{2.71 + 3.29\sqrt{R_b\ T_s\ (1 + \frac{T_s}{T_b})}}{K\ T_s}$$

where:
- R_b = background counting rate
- T_s = sample counting time
- T_b = background, or blank, counting time
- K = instrument efficiency

The MDA should be as low as possible. There are four methods available to reduce the MDA value, which include:

- Collecting larger samples
- Reducing the background
- Counting the samples longer
- Selecting a counting system with a greater efficiency

Lower Limit of Detection

Lower limit of detection (LLD) is another statistical value used due to the random nature of radioactive decay. The LLD is broadly defined as the smallest amount of activity that will yield a net count for which there is a predetermined confidence level for present activity.

The following formula calculates the LLD when background and sample count times are equal.

$$LLD = \frac{4.65\sqrt{\frac{R_b}{T_b}}}{E}$$

where:
- R_b = background counting rate
- T_b = background counting time
- E = instrument efficiency

Counting Efficiency

In order for the instrument to register a count, the radiation emitted must interact with the detector, deposit energy, and create an electrical signal. Most detectors miss some of the radioactive events or decays for a number of reasons (e.g., radioactive decay is isotropic, or radiates in a 360° sphere, resulting in only a small portion of the radiation being defected). In order to relate the counts registered on the instrument to the activity in the sample, the following formula is used:

$$Activity = \frac{counts}{\epsilon}$$

where:	Activity	=	bequerels or curies
	counts	=	counts registered on the instrument
	ϵ	=	instrument efficiency

As long as the instrument efficiency remains constant, the activity can be reliably calculated. Most instruments are actually only 1% to 40% efficient. However, gas flow proportional counters with 4 π (pi) geometry or liquid scintillators can approach 100% efficiency when counting alpha particles, because all of the energy of the decay is deposited in the active volume of the detector.

Counting Uncertainties

When calculating activity from an air sample, there is error associated with the flow rate of the pump, the filter collection efficiency, and with the counting system. To calculate the total uncertainty when multiple sources of error are involved, the following formula is used:

$$Total\ uncertainty = \sqrt{U_f^2 + U_e^2 + U_c^2}$$

where:	U_f	=	percent error in the flow rate
	U_e	=	percent error in the collection efficiency
	U_c	=	percent error in the counting system

Percent error in the counting system is a function of the error in the background count rate and the sample count rate. This error, calculated to the 95% confidence level, is given by the formula:

$$Counting_{e} = 1.96\sqrt{\frac{R_b}{T_b} + \frac{R_{s+b}}{T_{s+b}}}$$

where:
- R_b = background counting rate
- T_b = background count time
- R_{s+b} = gross sample count rate
- T_{s+b} = gross sample count time

Radiological Field Surveys

Surveys must be taken in the workplace for radiation fields, surface contamination levels, and airborne contamination levels. A general monitoring sequence for encountering an unknown radiological condition would be as follows:

1. Verify external exposure rates in the area, locate sources of radiation by using a/an:
   - ion chamber for gamma radiation
   - remball for neutron dose equivalent rates

2. Verify loose contamination levels on exterior surfaces
   - Smear survey (G-M, ZnS, or ion chamber with an open window)

3. Obtain or start an air sample

4. Verify fixed contamination levels against exterior surfaces
   - Direct frisk (G-M or ZnS)

<u>Radiation Fields</u>

In most cases external radiation fields have the highest potential hazard when approaching an unknown radioactive waste situation. There are three types of external radiation fields to be aware of, they are:
- Gamma
- X-Ray
- Neutron

Gamma Radiation Fields

The best overall portable instrument to quantify high gamma radiation fields is an ion chamber detector, such as Eberline's RO-2 and RO-2A. These instruments have ranges of 1 to 5,000 mR/hr and 10 to 50,000 mR/hr respectively.

The intensity of external radiation fields varies depending on the activity of the source, energies of the radiations emitted from the source, geometry of the source, distance from the source, and shielding materials. The intent of a survey is to verify the highest dose rate, which can be obtained at the source of the radiation.

Approach the unknown object by allowing the instrument to encounter the radiation field first. Have the instrument on its highest scale, watch the response of instrument and decrease the range of the instrument until the instrument responds, or the lowest range is reached.

Gamma radiation will be present in significant fields around:

- Spent nuclear fuel rods
- Reactor fission products
  - Cs-137 (problem because of relatively long 30-year half-life)
- Reactor activation products
  - Co-60 (problem because of 5.2 year half-life, high abundance in reactor water, strong gamma emission per disintegration)
- UF_6 cylinders
- Th-228, decay daughter of U-232

Reactor waste products that can be expected to have high gamma radiation fields are:

- Reactor clean-up and fuel pool clean-up systems
  - filter sludge
  - reactor clean up resins
- Primary reactor piping components
  - valves
  - internals of the main steam line system

Neutron Radiation Fields

Neutron radiation fields can be measured by a proportional counter known as a remball. The remball measures dose equivalent neutron fields in mrem/hr range and greater. While use of the remball will provide information on dose equivalent rate for safety purposes, it is not good for detection of small activity neutron sources. Smaller neutron fields may be detected by the use of a ZnS detector, taking advantage of the (n, alpha) reaction. Although the detector is not designed to measure neutrons, count rates as low as 60 cpm for thermal neutrons and 15 cpm for fast neutrons can be measured. The ZnS detector should be tested against low activity neutron sources to determine the efficiency of the instrument. Also, the instrument is modified by the use of a moderator to increase the efficiency for detection of neutrons.

Neutron radiation fields are found around the following situations:

- Operating nuclear reactors
- Neutron calibration sources
  - PuBe source
- Spent nuclear fuel storage areas
- Fissile materials storage areas and transuranic waste, including uranium as UF6
  - Uranium-235 (U-235)
  - Uranium-233 (U-233)
  - Plutonium-239 (Pu-239)

Neutron radiation fields increase with the level of enrichment in U-235. Some typical neutron radiation fields associate where large quantities UF6 are stored.

- < 5% enrichment of U-235
  - 0.01 to 0.2 mrem/hr
- > 97% enrichment of U-235
  - 2 to 4 mrem/hr

X-Rays, Measurements for Plutonium

Thin Nal and Phoswich detectors (a thin scintillator attached to a thick one) have been developed to measure low-energy x-rays (particularly those near 17 keV) from plutonium isotopes. The thin Nal detector and the thin scintillator in the Phoswich detector reduce the effects from higher energy gamma radiation and the thick detector in the Phoswich is used to eliminate remaining thin-crystal signals that occur simultaneously with pulses from the thick backup crystal. This maximizes the fraction of output that comes from the desired low-energy x-rays. These detectors are used to detect plutonium when the fraction of americium-241 (Am-241) is not known (Am-241 is more easily detected and can be used as a benchmark, if the relative amounts of Am-241 and plutonium are known) and when there is too much absorption to measure alpha radiation. This technique is limited, however, by absorption in the material because 1 cm of water will absorb about 80% of the incident x-rays.

Radioactive Surface Contamination

Radioactive surface contamination is classified as either fixed or removable.

Fixed Contamination

This contamination cannot be readily removed from surfaces. It cannot be removed by casual contact. It may be released when the surface is disturbed (buffing, grinding, using volatile liquids for cleaning, etc.) Over time it may "weep," leach, or otherwise become loose or transferable. Fixed contamination may be detected by direct frisk with a G-M tube for beta/gamma or a ZnS for alpha.

In order to survey for fixed contamination, place the G-M probe within 1/4 inch to 1/8 inch of the surface of the object, moving the probe about two to three inches per second. Any readings obtained could be the result of fixed or removable contamination on the outside of the object or small levels of gamma radiation inside the object. A localized fixed contamination reading on the surface of a large container can drop off drastically by moving the probe only six inches away from the surface. To verify fixed versus removable contamination, one should perform a smear survey.

Removable Contamination

Removable/transferable contamination can be readily removed from surfaces. It may be transferred by casual contact, wiping, brushing, or washing. Air movement across removable/transferable contamination could cause the contamination to become airborne.

Survey the exterior of the container by smearing the surface of the container with an absorbent material, then frisking the smear with a G-M detector. The background on the G-M detector should be less than 300 cpm. Smear areas that may have leaked radioactive material from inside the container. Specifically, smear areas around:

- Signs of leaks,
- Corrosion, e.g., rust of the container
- Pressure relief valves
- Seals

Compare the background on the G-M detector near the object with a low background area of 200 to 300 cpm. Increases in background, within a few feet of the container, most likely indicate the presence of gamma or x-ray radiation.

3. SELF-STUDY SCENARIOS/ACTIVITIES AND SOLUTIONS

Review

- 10 CFR 835, *Occupational Radiation Protection.*
- DOE/EH-0256T, *Radiological Control Manual*.
- DOE G-10 CFR 835/E2 (Revision 1), *Workplace Air Monitoring* (implementation guide).
- DOE/EH-0173T, *Environmental Regulatory Guide for Radiological Effluent Monitoring and Environmental Surveillance.*
- ANSI/ANS-8.3-1986, *Criticality Accident Alarm Systems*.

Actions or situations were combined to create new incidents for the following scenarios from these references:

- *Operating Experience Weekly Summary 96-24*, June 7 - 13, 1996, Event Number 1.
- *Operating Experience Weekly Summary 96-25*, June 14 - 20, 1996, Event Number 1.

Activity 1

During a routine test of the criticality alarm system, a DOE employee discovered that several of the facilities' audible alarms did not actuate. The employee found that wiring to the alarms had been accidentally broken while other electrical cables were being pulled through the cable run that contained criticality alarm wiring. The facilities' system provided indication, prior to the next scheduled test, that some of the audible alarms had been disabled.

Does the situation described above indicate compliance or noncompliance with the ANSI Standard (ANSI/ANS 8.3-1986)? [Section 5, Criteria for System Design; Section 6, Testing.] Specify the evidence you have to support your conclusion. What lessons can be learned from this situation?

Your Solution:

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Activity 2

Engineering drawings describing modifications at a DOE facility specified removal of “heat (radiation) detectors.’ Facility review of the modification package did not recognize that it included removal, rather than relocation, of criticality alarm system detectors. When the specified detectors were removed, no alarm was generated at the system monitoring panel. Subsequent investigation disclosed that the alarm panel was wired in such a way that, although a "failure" light was activated at an intermediate panel (an unmanned location), a loss of power/loss of detector signal was not generated at the monitoring panel in a normally manned area.

Does the situation described above indicate compliance or noncompliance with the ANSI Standard (ANSI/ANS 8.3-1986)? (Section 4, General Principles; Section 5, Criteria for System Design). Specify the evidence you have to support your conclusion. What lessons can be learned from this situation?

Your Solution:

Activity 3

A DOE facility experienced an activation of the plant's criticality alarm system, but no criticality had actually occurred. Investigation found that the alarm had been generated when the uninterruptible power supply (UPS) circuit that powered the alarm system was turned off by means of a switch in the facility's main computer room. The switch had been backfitted to the system to allow for cutoff of all power to the computer room in emergency situations and was not intended to affect power to the criticality alarm system. The modification review associated with the addition of the switch did not identify the fact that the planned location was between the UPS source and the primary criticality alarm system circuit.

Does the situation described above indicate compliance or noncompliance with the ANSI Standard (ANSI/ANS 8.3-1986)? (Section 4, General Principles; Section 6, Testing). Specify the evidence you have to support your conclusion. What lessons can be learned from this situation?

Your Solution:

Activity 4

During an electrical storm, the criticality safety alarms at only the DOE facility's waste treatment facility sounded because of a momentary power interruption. Personnel in the building did not evacuate, but instead called security, who in turn notified appropriate radiological control and electrical shop personnel. The electricians arrived at the building to silence the alarms without receiving clearance to do so. They entered the waste treatment facility and silenced the alarms.

Does the situation described above indicate compliance or noncompliance with the ANSI Standard (ANSI/ANS 8.3-1986)? (Section 4, General Principles). Specify the evidence you have to support your conclusion. What can be inferred from the personnel response in this case? What lessons can be learned from this situation?

Your Solution:

Activity 5

A test of a building's criticality alarm system was in progress when facility personnel found a subcontractor security inspector inside the building. During such tests, all unnecessary personnel were evacuated from the building and the entrance doors were locked to prevent entry. Flashing criticality warning beacons, mounted outside each entrance, were also activated during the surveillance test. Permanently posted instructions at each entrance warned people not to enter the building when the beacon was operating. The security inspector had entered the building using his security key, despite the flashing warning beacon and the written instructions. His action constituted a breach of administrative controls specified in the criticality alarm test procedure.

A lack of training was not considered to be at issue in this event.

Does the situation described above indicate compliance or noncompliance with the ANSI Standard (ANSI/ANS 8.3-1986)? (Section 6, Testing; Section 7, Employee Familiarization). Specify the evidence you have to support your conclusion. What lessons can be learned from this situation?

Your Solution:

Activity Solutions:

Activity 1, Solution
(Any reasonable paraphrase of the following will be acceptable.)

The situation described above indicates compliance with the ANSI standard. Routine tests were performed and the system provided indication of disabled audible alarms. This situation underscores the importance of problem indicators and the importance of conducting routine tests.

Activity 2, Solution
(Any reasonable paraphrase of the following will be acceptable.)

The situation described above indicates noncompliance with the ANSI standard. No alarm was present at the monitoring panel upon the removal of the detectors. In addition, the alarm panel was not correctly wired to ensure activation at a manned location. Also, loss of power would not have been noticed at the manned location. Lessons learned include the following:

- Modifications to areas requiring criticality accident alarms should be carefully reviewed.
- Failure lights or indicators must be activated in manned areas.
- The design did not consider double contingency implications.
- The safety review committee should pay more attention to what they are reviewing.
- Safety systems need special attention.

Activity 3, Solution
(Any reasonable paraphrase of the following will be acceptable.)

The situation described above indicates noncompliance with the ANSI standard. Loss of power resulted in a false alarm. In addition, there was no apparent testing of the system after the modification. Lessons learned include the importance of a modification review specifying criticality accident alarm concerns and the importance of testing following modifications.

Activity 4, Solution
(Any reasonable paraphrase of the following will be acceptable.)

The situation described above indicates noncompliance with the ANSI standard. A false alarm resulted from the momentary loss of power. Personnel do not always follow procedures. Frequent false alarms lessen the response of personnel to potential emergency situations. Personnel may need to be "overtrained" to respond to emergency alarms. The main lesson is that it is very important to have battery backup to avoid false alarms.

Activity 5, Solution
(Any reasonable paraphrase of the following will be acceptable.)

The situation described above indicates compliance by the facility. Compliance occurred because tests were being conducted and signs were permanently posted. Lessons learned include, that some people do not believe the rules apply to them. Also, the severity of the consequences of not following procedures needs to be emphasized.

4. SUGGESTED ADDITIONAL READINGS AND/OR COURSES

Readings

- 10 CFR 835, *Occupational Radiation Protection*
- DOE N 441.1, *Radiological Protection for DOE Activities*
- DOE/EH-0256T (Revision 1), *Radiological Control Manual*

  NOTE: See Appendix 3A, Checklist for Reducing Occupational Radiation Exposure, pp. 3-35 & 3-36
- DOE Order 5480.4, *Environmental Protection, Safety, and Health Protection Standards*
- G-10 CFR 835/E2, Revision 1, *Workpace Air Monitoring, Implementation Guide for Use with Title 10 Code of Federal Regulations 835*
- International Commission on Radiological Protection. *Cost -Benefit Analysis in the Optimization of Radiation Protection* (ICRP 37). New York: Author.
- International Commission on Radiological Protection. *Recommendations on the International Commission of Radiological Protection* (ICRP 60). New York: Author
- Pacific Northwest Laboratory. (1988). *Department of Energy Health Physics Manual of Good Practices for Reducing Radiation Exposure to Levels that are As Low As Reasonably Achievable (ALARA)* (PNL-6577). Richland, WA: Author.

Courses

- DOE/EH-0450 (Revision 0), *Radiological Assessors Training (for Auditors and Inspectors) - Fundamental Radiological Control,* sponsored by the Office of Defense Programs, DOE.
- *Applied Health Physics* -- Oak Ridge Institute for Science and Education.
- *Health Physics for the Industrial Hygienist* -- Oak Ridge Institute for Science and Education.
- *Safe Use of Radionuclides* -- Oak Ridge Institute for Science and Education.
- *Radiation Protection Functional Area Qualification Standard* -- GTS Duratek.