Radiation Detection and Dosimetry and Radiation Detector Calibration

Nevada Technical Associates

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Acknowledgements

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Introduction

Ionizing radiation is heavily regulated and is potentially hazardous. For these reasons, it is essential to have accurate ways to measure our exposure to radiation, the amount of radioactive contamination present in the workplace and the environment, and to be able to monitor the radiation dose to which people are exposed. If we are to measure these with any degree of confidence, we must be confident that our instruments are providing us with accurate information, and we must understand the accuracy of the information presented to us. For these reasons, we not only need to be able to have access to radiation detectors; we must also be able to calibrate our instruments and to perform statistical analyses on the data produced.

The first radiation detectors were developed early in our history of using radiation. In the intervening century, these initial designs have proven remarkably resilient and many of the instruments we use today are virtually identical to some of the first radiation detectors used. In the last century we have, of course, designed new types of radiation detectors, the field of personal dosimetry has become remarkably advanced, and earlier instrument designs have been refined almost beyond recognition. However, the basic principles of radiation detection remain the same – we are detecting the energy deposited in a medium by ionizing radiation and, in some cases, we are analyzing specific characteristics of that energy deposition to obtain specific information about isotopic composition, dose rate, and other parameters.

There are a number of methods of detecting radiation, most of which rely on radiation’s ability to create ion pairs in irradiated materials. Devices such as Geiger counters and ion chambers detect these ionizations directly and measure the electric current generated by radiation bombardment. Other devices, such as scintillation counters, detect photons that are emitted when a substance is irradiated, amplifying these photons in photo-multiplier tubes to create a signal. The most commonly-used of these detectors are described in the following section.

Counting geometry

The surface area of a sphere is equal to $4\pi$ steradians, so a counter that completely surrounds the sample has $4\pi$ counting geometry. In this geometry, all radiation emitted by the sample has the potential to be counted, so $4\pi$ geometry has the highest counting efficiency. A handheld meter can cover one half of the possible area, so a handheld probe has $2\pi$ counting geometry.

Laboratory instruments can have $4\pi$ counting geometry by completely immersing the sample in the counting medium or by completely surrounding the sample by the counter. For example, in a liquid scintillation counter the sample is dispersed in (sometimes dissolved into) liquid scintillation cocktail. In a $4\pi$ proportional counter, the sample is suspended in the counting chamber and, again, virtually every disintegration has the potential to be counted.
Atoms are the fundamental units of nature. They bond together to form chemical compounds. The sizes of atoms range from one tenth of an angstrom to nearly two angstroms ($10^{-8} \text{ cm}$).

Atomic nuclei are composed of protons and neutrons. The number of protons present determines an atom’s chemical properties. Protons all have a positive charge, so they tend to repel each other electrically. Because of this, neutrons are needed to help hold an atom together — neutrons carry the strong nuclear force that overcomes the electrostatic repulsion of the protons. The strong nuclear force has a very short range so, as an atom increases in size, more neutrons are needed to stabilize the nucleus. When neutrons are added to or subtracted from an atomic nucleus, the energy level of the nucleus is altered and the atom may become unstable. So, for example, a carbon atom with 6 protons and 6 neutrons is stable carbon-12 while a carbon atom with 6 protons and 8 neutrons is unstable carbon-14. Carbon 12 and -14 are called two isotopes of carbon because they have the same number of protons but different numbers of neutrons.

The two major intrinsic properties of these particles are their mass and their electric charge as these both have a bearing on their interactions with matter and their ability to cause damage. The higher the charge and the more mass that a particle contains, the more damage that it can do.

Electrons are the lightest of these particles. They carry a charge of -1 and have a mass of one two-thousandth that of the proton or neutron. They can interact with matter either by direct ionization, or by bremsstrahlung. High energy electrons are referred to as beta radiation.

Direct ionization consists of an electron striking an atom and knocking loose one of that atom's electrons. This creates an ion pair (a positively charged atom and a negatively charged electron) that can go on to cause more ionizations within the cell. Bremsstrahlung is German for "braking radiation" and is caused by an electron passing near to a heavy atom. The atom and electron interact electrostatically, the atom deflecting the electron which gives off radiation (usually in the x-ray region) as it changes course. A thin lead shield that is placed around a beta source will shield all of the beta radiation but will emit x-rays due to bremsstrahlung. Beta radiation is weakly penetrating and usually constitutes a skin dose only, although the lens of the eye is also susceptible. Due to its low mass and charge of -1, the beta can be shielded by plastic.

The number of ionizations caused by beta radiation is proportional to the energy (velocity) of the beta radiation and to the mass of the atoms that it is passing through. So, in general, higher-energy beta particles will cause more ionizations and those that are interact with heavier atoms will cause more bremsstrahlung x-rays (described later).

Another type of particulate radiation is the alpha particle. Alpha particles are helium atoms that have had their electrons removed, giving them a charge of +2. They are also massive
with a mass of 4 amu. This means that they are capable of causing more damage than any other form of radiation but that they are also far less penetrating. A piece of paper is an adequate alpha shield and they generally cannot penetrate the dead layer of skin that we all have. This strong interaction with matter makes alpha particles a concern for internal dose only.

A third form of radiation is the gamma ray, a high-energy photon that is given off by atomic nuclei that have been excited by beta emission, neutron capture, electron capture, or some other means. Most radioactive decays will produce gamma radiation. An atomic nucleus contains protons and neutrons in discrete energy states, much like the electrons surrounding it. During radioactive decay, the decay particles carry off energy. Unless this energy is the exact amount needed for transition to the next lower energy level, the nucleus is still in an excited state. The nucleus will de-excite by emission of a gamma containing the energy difference between the energy state that the nucleus is in and the next lower energy level. There are a few nuclides, such as tritium (H-3) that emit a particle containing the exact amount of radiation that is required for this transition to a stable configuration; the rest of the nuclides will emit gamma radiation when they decay.

Gammas have no mass and no charge and interact by either direct collision with electrons, knocking them out of their orbits (the photo-electric effect), production of an electron-positron pair if it passes near a heavy nucleus (pair production), or by absorption and re-emission by an atom, usually in a different direction and at a different energy (Compton scattering). Photons interact very weakly with matter and are best shielded by dense materials such as lead. Photons, along with neutrons, are considered to be a whole-body dose as they will penetrate through the entire body.
Choosing the correct instrument: a case study

The following text is taken from a report submitted to a client in early 2003. This excerpt has been “sanitized” by removing information that could serve to identify my client. The problems noted in this report are not uncommon, even among experienced health physicists.

Review of instrument calibration records and instrument use
Instrument calibration records indicate that radiation detection instruments at this facility are calibrated using a 1.2 Ci Cs-137 source. The calibration certificates indicate that the calibrations performed are dose rate calibrations. All instruments (NaI, GM “pancake”, and energy-compensated GM) have dose rate scales on the meter face, and the latter two instruments also have count rate scales. However, the calibration certificates do not indicate count-rate calibrations were performed on these meters and do not provide count rate calibration information. This suggests that the meters are not calibrated for use as count rate instruments and it may not be appropriate to use them in this manner. In conversation with staff, it appears as though all instruments are commonly used to measure dose rates, and the GM and energy-compensated GM are also used to monitor for contamination. There are some potential problems with this use, as described below.

1. Radiation dose rate is a measure of energy deposition per unit time in a given mass of material. Geiger counters cannot distinguish between the energy of incident radiation and, in fact, cannot distinguish between different types of radiation. This means that a GM detector calibrated with Cs-137 as a dose rate instrument can only reliably provide dose rate measurements when the source of radiation is Cs-137; it is not appropriate to use such a meter to measure radiation levels from isotopes with different energy radiation because the dose conversion factor for each type of radiation is different. As one example, a meter calibrated for Cs-137 will read high by a factor of 4-5 if used to measure Tc-99m, will read low by a factor of 4 if used to measure Co-60, and will respond completely inaccurately to Y-90 because this isotope emits high-energy beta radiation that is only a skin dose. It is not uncommon for Geiger counters that are used in dose rate measurements to be assigned correction factors to allow their use with a variety of isotopes. Such information is not provided for these instruments.

2. The GM detectors are used to monitor for contamination, which is typically recorded in units of counts per minute (CPM) and then converted to disintegrations per minute (DPM) by using meter efficiency. CPM calibrations are usually performed by using an electronic pulser to input a given count rate to the instrument, and the instrument is adjusted so that this count rate is reflected in the meter reading. Count rate calibrations are usually performed at 1/3 and 2/3 full scale on all scales that are typically used. In addition, to properly record contamination levels in units of DPM (which is required by regulations), it is essential to have measured the detection efficiency for the meter being used with the isotope in question. For example, at my place of employment we calibrate Geiger counters using a pulser and we calculate detection efficiencies using a variety of alpha, beta, and gamma sources with varying energies of radiation. Our calculated efficiencies vary from about 0.5% to 45%,
depending on the detector used and the isotope being measured. Without this efficiency information, it is not appropriate to record contamination levels in any units other than CPM. *(Note: Calibrations performed by the same vendor on the hand and foot monitors are performed using a pulser to calibrate to a given count rate. Also, the 1997 and 1998 calibrations for instrument #99628 were performed to the standards noted above in that the instrument was calibrated electronically on all scales and detection efficiencies for a variety of isotopes were measured and plotted on an attached graph.)*

3. From reading the calibration records and from speaking with some facility staff that it is not uncommon to measure dose rates by turning the back of the probe towards the source of radiation. This is also noted in the calibration notes – that “Pancake probes are calibrated to the back of the probe.” Prior to this visit, I had not heard of this practice, and I must admit I am dubious as to its effectiveness as a general calibration practice. In particular, my concerns about using a pancake GM for any dose rate measurements remain, and I am also uncertain with regards to the transmission of radiation through the back of the detector and whether or not this can be used as a reliable indication of radiation dose rate.

4. As a corollary of the above, I noted that radiological surveys are not always recorded appropriately. Specifically, many contamination surveys (e.g. ring badges, vehicle) are recorded in units of mr/hr, which is not appropriate for determining compliance with regulations that specify contamination levels in units of dpm/100 cm$^2$. It is more appropriate to record such results in units of CPM and to calculate a corresponding DPM using the meter efficiency for the particular isotope of concern.

5. In conversation with the corporate Health Physicist I confirmed that he advises against using the GM pancake probe for making dose rate measurements. Such measurements should only be performed with an appropriate detector, such as an energy-compensated GM. Mr. Krueger also mentioned that the forms on which contamination survey measurements are made will be changed in the near future so that they are easier to maintain and request appropriate information. In particular, he noted that the intent of many survey forms is to obtain both dose rate and count rate information, and that dose rate information should be obtained with an energy-compensated GM while count rate information (from direct frisk or from smear wipe surveys) should be obtained by counting smear wipes in a well counter or with a GM frisker. Accordingly, I recommend changing the current radiological survey practices to include performing all surveys with appropriate instruments and recording this information in appropriate units of mr/hr for radiation area surveys and cpm (converted to dpm) for contamination surveys.

6. In conversations with the instrument calibration facility, I confirmed that the GM detectors can be calibrated for either dose rate or count rate, but not for both. In the absence of a specific request for a count rate calibration, his default was to perform a dose calibration. I recommend specifically requesting the GM pancake probe be calibrated for count rate measurements in all future calibrations.
Radiation Detection
Instrumentation and Personal Dosimetry
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Types of measurements

• Dose rate
• Count rate
• Spectroscopy
• Personal dosimetry (integrated dose)
Types of detectors

- Gas-filled detectors
  - G-M tubes
  - Ion chambers
  - Proportional counters
- Scintillation-type detectors
  - α, β, γ detectors
  - Micro-R meters
  - Liquid scintillation counters
- Personal dosimeters
Gas-filled detectors: Geiger counters, ion chambers, proportional counters

In gas-filled radiation detectors, a fill gas (often argon, propane, or air) is enclosed in a chamber that has an electrical potential applied across it. As ionizations occur in the fill gas, the ion pairs move to the anode and cathode under the influence of this electrical potential difference. As the electrons move through the circuit connecting anode and cathode, they create a signal that is measured to provide an output signal that can be related to various parameters (count rate, radiation dose rate, etc.).

As the voltage applied across the chamber changes, the response of the chamber to ionizing radiation changes. Different radiation instruments make use of various parts of this curve so, although both Geiger counters and ion chambers are both gas-filled detectors, they provide different types of information.

G-M Tubes

G-M tubes are sealed, gas-filled tubes containing an anode and a cathode with a large voltage applied across them. The interaction of ionizing radiation with this gas causes secondary ionizations to occur, creating a current spike as the positive ions are attracted to the anode and the negative ions to the cathode. This current is amplified and registers as a count on the meter. The ionized gas will quickly recombine, allowing detection of the next ionizing event. There is a small amount of "dead time" while this recombination is taking place, usually in the neighborhood of 1-2 usec, during which no counting can take place. This imposes an upper limit on the count rate for which the instrument can theoretically be used, in this case, 200,000 cpm. The disadvantage of a G-M tube is that there is, however briefly, a period during which no counts can be registered. This also allows for the tube to become "saturated" and not register accurately if the count rate is too great. The chief advantages of the G-M tube are its extreme simplicity, leading to great reliability, and its high sensitivity.

In general, GM counters are not useful for radiation dose rate measurements because every ionization results in complete ionization of the fill gas. This means that a low-energy event will create a signal identical to a high-energy event. Since radiation dose is a measure of energy deposition, this makes a Geiger counter unreliable for dose-rate measurements unless the radiation field is well-characterized with respect to gamma energies. Energy compensated GM detectors can compensate for this if they are used, but they may be less sensitive to contamination levels because the probe cross-sectional area is often much less than that of a "pancake" GM probe.

Geiger-Muller tubes are primarily used for the detection of gamma and beta radiation and measure in Roentgen (Rad) per hour.
**Pulse height versus voltage**

**Explanation of figure**

- **Region A: Recombination region**
  - recombination of positive ions and electrons occurs so that not all ion pairs are collected.

- **Region B: Ionization Chamber Region**
  - only a small amount of recombination occurs.

- **Region C: Proportionality Region**
  - electrons approaching the center wire attain sufficient energy between collisions with gas atoms to produce new ion pairs. A limited cascade takes place. The total charge passing through R may be up to 1000 times the charge produced initially by the radiation.

- **Region D: Limited proportionality region**
  - The proportionality feature is lost.

- **Region E: Geiger-Muller Region**
  - Even a minimally-ionizing particle will produce a very large voltage pulse. Ionization process spreads along the total length of the centre wire, partly involving electrons as intermediaries. The initial ionization triggers a complete gas breakdown. Gas breakdown must be stopped (quenched) in order to prepare for a new event

- **Region F**
  - Spurious untriggered breakdowns start to occur and a continuous unquenchable discharge results.
Air Ionization Chambers

The ion pairs created in the detector are collected and measured before they can recombine. This gives an output current that is proportional to the strength of the radiation field.

Air ionization chambers are open to the atmosphere. An advantage of this design is that the chamber, not being pressurized, cannot spring leaks. However, this makes the chamber sensitive to environmental conditions and to differences between locations of calibration and use. This is because the amount of energy required to generate a given degree of electrical current depends on the number of atoms (ionization targets) per unit volume in the chamber and on the ionization potential for each of those atoms. At high elevations, the air is thinner and is often dry, so the ionization characteristics of the air are different from those at sea level in a tropical location (where the air is denser and moisture-saturated). Accordingly, an air ionization chamber calibrated in the high desert will probably not read accurately in Florida, and vice versa. In such instances, it is sometimes necessary to calculate a correction factor for use in the new location. Air ionization chambers are reliable, once atmospheric conditions are taken into effect, but they are not highly sensitive to low levels of radiation and, in most cases, are not useful in radiation fields less than a few mR/hr.

Pressurized ion chambers are sealed chambers that are pressurized to anywhere from 2 to 25 atmospheres, often with argon. Since the chamber is pressurized and isolated from the atmosphere, there is no need to perform altitude or humidity corrections, and the higher number density of atoms in the chamber make it more sensitive to low radiation levels. Some PICs can reliably quantify radiation levels as low as a few micro-rad/hr; much more sensitive than air ionization chambers. However, they are susceptible to leaks, and a leaking PIC is unusable until repaired. This can make them more expensive to maintain and can give them a reduced availability.

The advantages of the air ionization chamber are that the output current (the meter reading) is largely independent of the operating voltage and that they are, for the most part, easy to use and very portable.

Proportional counters
Proportional counters operate in a region of the response curve in which the output signal is proportional to the energy deposited in the gas and to the applied voltage. This means that, for a constant voltage, the output pulse will be higher as the energy of the interaction increases. Since most alpha radiation has a much higher energy than beta radiation, a proportional counter can be used to simultaneously measure both alpha and beta radiation by sorting pulses into one of two “bins” – the high-energy alpha bin and the lower-energy beta bin – by means of a pulse height discriminator.

Proportional counters are frequently used in the laboratory and, less frequently, in the field. Field surveys for tritium, for example, are almost always performed using a hand-held
proportional counter. In the laboratory, proportional counters are often used for gross alpha-beta measurements, a screening measurement.

The most common type of proportional counter is a gas-flow device, in which a constant flow of gas (usually propane) passes through the detector chamber. In such devices, it is important to monitor the level of gas in the tank so that the proportional counter works properly.

Hand-held proportional counters usually have 2 p counting geometry, and some laboratory counters can have nearly 4 p counting geometry.
Gas-filled detectors
Gas-filled detectors

- Consist of a gas-filled chamber, across which an electrical potential difference is maintained
- Ions created in the chamber generate an electrical signal that is measured as a count or a dose rate
Radiation Detection
Gas Filled Detectors

Incident Ionizing Radiation

Voltage Source

Electrical Current Measuring Device

Anode +

Cathode -

Air or Other Gas
Pulse height versus voltage

Diagram showing the relationship between pulse height and DC voltage, with labeled regions A through F.
Explanation of figure

- **Region A: Recombination region**
  - Recombination of positive ions and electrons occurs so that not all ion pairs are collected.

- **Region B: Ionization Chamber Region**
  - Only a small amount of recombination occurs.

- **Region C: Proportionality Region**
  - Electrons approaching the center wire attain sufficient energy between collisions with gas atoms to produce new ion pairs. A limited cascade takes place. The total charge passing through R may be up to 1000 times the charge produced initially by the radiation.

- **Region D: Limited proportionality region**
  - The proportionality feature is lost.

- **Region E: Geiger-Müller Region**
  - Even a minimally-ionizing particle will produce a very large voltage pulse. Ionization process spreads along the total length of the centre wire, partly involving electrons as intermediaries. The initial ionization triggers a complete gas breakdown. Gas breakdown must be stopped (quenched) in order to prepare for a new event.

- **Region F: Spurious untriggered breakdowns start to occur and a continuous unquenchable discharge results.**
### Specific Ionization in Air at Standard Temperature and Pressure

<table>
<thead>
<tr>
<th>Radiation Energy (MeV)</th>
<th>Ion Pairs Produced/cm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Alpha</strong></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>55,000</td>
</tr>
<tr>
<td>6</td>
<td>40,000</td>
</tr>
<tr>
<td><strong>Beta</strong></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>110</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
</tr>
<tr>
<td>3</td>
<td>75</td>
</tr>
<tr>
<td><strong>Gamma</strong></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>2.5</td>
</tr>
<tr>
<td><strong>Neutron</strong></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

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GM tubes

- Apply high voltage to gas
- Radiation causes complete ionization of gas, giving a count on the meter
- There is short “dead time” after each count, so tube can saturate
- Three types of probe – “pancake”, “hot dog”, and energy-compensated
- Used for contamination and radiation surveys
What GM detectors look like
GM limitations

- Not energy-sensitive (except for energy-compensated GM)
- Dead time means that very high count rates can saturate tube
- Not sensitive to low-energy betas and gammas
GM benefits

- Relatively simple and inexpensive
- Relatively rugged
- Relatively constant efficiency across a variety of radiation energies
GM uses

- Pancake probe very good for contamination surveys
- Hot dog probe useful for radiation surveys, provided properly calibrated
- Energy-compensated GM good for radiation level surveys
Proportional counters

- Radiation interactions cause spike in voltage reading
- Size of spike is proportional to radiation energy
- Since $\alpha$ particles are more energetic than betas, can use same detector to count and $\beta$ radiation simultaneously
- However, need constant flow of gas (propane) to function properly
Some proportional counters
Counting geometry

- Proportional counters can give nearly $4\ p$ geometry.
- "$4\ p$" means that the sample is completely surrounded by the counting medium.
  - Comes from the surface area of a sphere, which is equal to $4\ p$ steradians.
- Counting on a flat surface is $2\ p$ geometry.
Counting efficiency

- Beta counting efficiency varies with beta energy
  - ~5% for C-14 ($E_{\text{max}} \sim 150$ keV)
  - ~40% for P-32 ($E_{\text{max}} \sim 1.7$ MeV)
Backscatter curves
Beta radiation measurements

- Beta particles need to enter detector to register as a count
- The thickness of the detector window and walls can affect sensitivity and efficiency
  - Betas can't penetrate high thickness, are not counted
### Beta source sets

Beta Emitting Radionuclides Suitable for Calibration for the Measurement of Surface Contamination

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Emax (MeV)</th>
<th>Half-Life (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-14</td>
<td>0.156</td>
<td>5730</td>
</tr>
<tr>
<td>Tc-99</td>
<td>0.294</td>
<td>215000</td>
</tr>
<tr>
<td>Cl-36</td>
<td>0.710</td>
<td>501000</td>
</tr>
<tr>
<td>Tl-204</td>
<td>0.764</td>
<td>38</td>
</tr>
<tr>
<td>Pb-210/Bi-210</td>
<td>1.66</td>
<td>22.3</td>
</tr>
<tr>
<td>Si-32/P-32</td>
<td>1.71 (P-32)</td>
<td>106</td>
</tr>
<tr>
<td>Si-90/Y-90</td>
<td>2.28 (Y-90)</td>
<td>26.6</td>
</tr>
<tr>
<td>Sr-90</td>
<td>0.546 (Sr-90)</td>
<td></td>
</tr>
<tr>
<td>Ru-106/Rh-106</td>
<td>3.84 (Rh-106)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>0.039 (Ru-106)</td>
<td></td>
</tr>
</tbody>
</table>
Ion chambers

- Radiation causes ionizations in chamber
- Ionizations create electrical current, and strength of current is related to radiation dose rate
- Used to measure radiation levels
- Sensitivity does not depend on radiation energy
- Pressurized ion chamber more sensitive and respond faster, but can develop leaks
Dose rate measurement

• We know the amount of energy required to create an ion pair in the chamber
• We know how much electrical current flow results from each ionization
• Therefore, by measuring the electrical current flow, we have an indirect measure of the amount of energy deposited in the chamber
• Radiation dose is a measure of energy deposition, so this tells us the dose to the chamber
Types of ion chambers

- Air ionization chamber – open to local atmosphere, subject to environmental effects such as humidity and air pressure
- Pressurized ionization chamber – sealed and pressurized, not susceptible to environmental changes
Air ionization chamber

- May need to account for difference in altitude and humidity between calibration location and location of use
- Not very sensitive at low dose rates due to low number density of air atoms
- Changing weather at the use location can affect sensitivity and performance
Pressurized ionization chamber

• Sealed chamber reduces sensitivity to changes in weather or location
• Pressurization increases number density of atoms in chamber, makes it more sensitive to low dose-rate fields
  – Some chamber pressurized up to 25 atmospheres with argon
• However, are more expensive and can spring leaks
Scintillation-type detectors

Another common means of measuring radioactivity is the scintillation counter. The passage of a beta or alpha particle through a scintillating medium will cause the emission of photons from the scintillant. These photons leave the scintillation medium and interact with one or more photo-multiplier tubes (P-M tubes) to register as counts.

An advantage of scintillation counters is their lack of dead time, making their major operational limit the speed at which the electronic components can operate. For example, a pulse will propagate through a sodium iodide (NaI) crystal in about 230 nsec, giving this detector a fundamental “speed limit” of about 4 million counts per second. Although this is slower than the speed of high-speed CCD circuitry, it is faster than the speed of the photo-multiplier tubes and simpler electronic circuits that comprise most radiation detectors, so the “speed” of the scintillation crystal itself is not the factor limiting the speed of the detector assembly.

A disadvantage to scintillation detectors is that the scintillating medium must be kept dark at all times. Even a tiny pinhole can admit enough light to ruin not only the reading but the detector. In addition, some detector crystals can be relatively fragile, particularly when thermally cycled (for example, performing outside surveys in the winter can lead to several “freeze-thaw” cycles daily).

Scintillation detectors are versatile and have a number of uses. As in ionization chambers, we know the amount of energy required to create a scintillation photon in the detector crystal, so counting the number of photons contained in each pulse tells us how much energy was contained in the interaction giving rise to that pulse. For alpha and beta scintillation counting, we can safely assume that all of the energy of the incident particle was deposited in the scintillation medium, so this is a direct measure of the energy contained in the particle. This means that, in principle, we can identify the isotope(s) in question by this means. Real life, however, is not quite as simple.

Gamma rays, for example, may not deposit all of their energy in the crystal; high-energy gammas may simply pass through the crystal without interacting at all, or interacting only slightly. This is a problem in small crystals primarily. In addition, gamma rays may scatter out of the crystal, or they may be degraded in energy to a certain degree at which point they are simply absorbed by an electron and stop creating scintillation photons. However, in general, if the detector crystal is sufficiently large, these effects are not so significant as to preclude isotope ID.

On the other hand, alpha and beta particles are much less penetrating than gamma rays, so when they enter a scintillant, it is very likely that all their energy will be deposited. However, this same relatively weak penetrating ability means that they can lose significant energy simply escaping from the media they are contained in, passing through a small air gap, and passing through the detector window. This self shielding is an especial problem with thick samples.
Inorganic crystals include lithium iodide (LiI), sodium iodide (NaI), cesium iodide (CsI), and zinc sulfide (ZnS). Inorganic crystals are characterized by high density, high atomic number, and pulse decay times of approximately 1 microsecond. Thus, they exhibit high efficiency for detection of gamma rays and are capable of handling high count rates.

Organic scintillation phosphors include naphthalene, stilbene, and anthracene. The decay time of this type of phosphor is approximately 10 nanoseconds. This type of crystal is frequently used in the detection of beta particles.

Plastic phosphors are made by adding scintillation chemicals to a plastic matrix. The decay constant is the shortest of the three phosphor types, approaching 1 or 2 nanoseconds. The plastic has a high hydrogen content; therefore, it is useful for fast neutron detectors.
Scintillation devices
Nal scintillation detectors

- Crystal emits photons during interactions with gamma rays
- Photons travel to photo-multiplier tube, which amplifies signal
- Sensitive to gamma radiation
- Used for contamination and radiation surveys for gamma emitters
- Also used for nuclide ID (when used with multi-channel analyzer)
Nal detector sizes

- Thin-crystal (1” x 1mm) – used for low-energy gammas (10-100 keV)
- Thick-crystal (1”x1”) – used for high-energy gammas (100+ keV)
- Thicker crystals available (2”x2”, 3”x3”, and larger sizes)
- Background counts increase as crystal size increases – up to 14,000 cpm for a 3”x3”)
**Nal limitations**

- Not sensitive to alpha or beta radiation
- Often have low efficiency
- Usually have higher background counts than GM tubes (harder to detect low levels of contamination)
- Crystals are fragile and thermally sensitive
Nal benefits

- Can have very large crystals to increase sensitivity
- Can be used to identify isotopes by looking for a specific gamma energy
- Can be used to measure radiation levels because # photons is proportional to gamma energy
Nal uses

- Nuclide ID and gamma spectroscopy
- Radiation levels (usually as part of a micro-R meter)
- Gamma contamination measurements
- Can be used to measure beta emitters via bremsstrahlung emitted from betas interacting in crystal, but not reliable
Nal detectors
Beta scintillators

- Usually plastic – most often anthracene or stilbene
- Need not be very thick due to relatively short range of beta particles in matter
  - Even high-energy betas have a range of only 1 cm in plastic
- Can measure beta dose rate or contamination levels
Liquid scintillation counters

- Used to count β emitters
- Sensitive to very wide range of beta energies
- Can be self-correcting for counting efficiencies (give DPM readout)
- Can be tricked by static electricity and chemical luminescence
- Can be expensive ($40 K or more)
Alpha counting – ZnS crystals

- Only used to measure alpha radiation
- Crystals are sensitive to shock
- Efficiency is typically low
- Alpha counting subject to self-absorption
Alpha probes

• Due to very short range of alpha particles, probe must be covered with very thin window, which is easily punctured, even though protected somewhat
• If window is punctured, will see increased count rate due to exterior light
• Can cover up to about 10% of window with dark tape or india ink if necessary
### Alpha calibration sources

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Energy (MeV)</th>
<th>Half-life (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gd-148</td>
<td>3.18</td>
<td>90</td>
</tr>
<tr>
<td>Th-230</td>
<td>4.6-4.7</td>
<td>77,000</td>
</tr>
<tr>
<td>Pu-239</td>
<td>5.15</td>
<td>24,000</td>
</tr>
<tr>
<td>Po-210</td>
<td>5.3</td>
<td>0.38</td>
</tr>
<tr>
<td>Pu-238</td>
<td>5.5</td>
<td>87.8</td>
</tr>
<tr>
<td>Am-241</td>
<td>5.5</td>
<td>433</td>
</tr>
<tr>
<td>Pu-212</td>
<td>8.78</td>
<td>10.64 hours (Pu-212)</td>
</tr>
</tbody>
</table>
## Properties of various scintillators

<table>
<thead>
<tr>
<th>Scintillator material</th>
<th>Radiations detected</th>
<th>Light output (photons per MeV)</th>
<th>Max emission wavelength (nm)</th>
<th>Decay constant (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaI(Tl)</td>
<td>?</td>
<td>38,000</td>
<td>415</td>
<td>230</td>
</tr>
<tr>
<td>CsI(Tl)</td>
<td>?</td>
<td>65,000</td>
<td>540</td>
<td>680</td>
</tr>
<tr>
<td>CsI(Na)</td>
<td>?</td>
<td>39,000</td>
<td>420</td>
<td>460</td>
</tr>
<tr>
<td>YAP</td>
<td>?</td>
<td>18,000</td>
<td>370</td>
<td>27</td>
</tr>
<tr>
<td>LSO</td>
<td>?</td>
<td>25,000</td>
<td>420</td>
<td>47</td>
</tr>
<tr>
<td>LuAP</td>
<td>?</td>
<td>17,000</td>
<td>365</td>
<td>17</td>
</tr>
<tr>
<td>ZnS(Ag)</td>
<td></td>
<td>49,400 (based on photo-electron yield)</td>
<td>450</td>
<td>200</td>
</tr>
<tr>
<td>Anthracene</td>
<td>B</td>
<td>87,400</td>
<td>447</td>
<td>30</td>
</tr>
<tr>
<td>Stilbene</td>
<td>B</td>
<td>43,700</td>
<td>410</td>
<td>4.5</td>
</tr>
</tbody>
</table>
Neutron survey meters
Spectroscopy (α, β, ?)
Basic principle

- Each alpha and gamma-emitting nuclide emits radiation with a discrete energy
- Beta-emitters emit a range of energies with a characteristic energy distribution
- By measuring the energy distribution of radiation emitted, we can identify the isotopes in question
  - Need to have all gamma energy deposited in detector for gamma spec to work properly
  - May be difficult in high count-rate due to overlapping events
Gamma spectroscopy

- In a scintillation detector, the number of photons released is directly proportional to the amount of energy deposited in the detector medium.
- By “counting” the number of photons in each event, we can estimate the energy of the incident gamma ray photon.
- Using this information, a histogram is plotted showing the number of events in each energy channel.
- By accumulating a large number of such events, we can identify the isotope(s) that are present.
Some gamma ray energies

- Co-60 1.1 and 1.3 MeV
- Cs-137 662 keV
- I-131 365 keV
- K-40 1.46 MeV
- U-235 185 keV
- I-125 30 keV
- Am-241 60 keV
Difficulties with gamma spec.

- Background radiation has its own spectrum – need to differentiate between background and your “signal”
- Most gamma spec materials have either low detection efficiency or low energy resolution
- Some isotopes have multiple gamma energies and some gamma energies are very similar between isotopes
Gamma spec detectors

• Sodium iodide
  – Room temperature, good efficiency, poor energy resolution
• High-purity germanium
  – Cryogenic, poor efficiency, excellent energy resolution
• Cadmium-zinc-tellurium
Example gamma spectrum
Beta “spectroscopy”

- Difficult to perform since beta particles from the same element can have a range of energies.
- However, each element has a maximum (“endpoint”) beta energy that is characteristic.
- Can sometimes ID beta-emitting isotopes by the endpoint energy, spectrum shape, and expected isotopes, but this is as much of an art as a science.
A typical beta spectrum

![Beta Spectrum Diagram]
Other detectors

- Neutron detectors (fast and thermal neutrons)
- HPGe gamma spectroscopy units
- Alpha spectroscopy (multiple types)
- Radon detectors
- High-pressure pressurized ion chambers (up to 25 atmospheres)
- Whole-body counters
- More....
Radiation dosimetry

There are several types of personnel dosimetry. Two major types, the Thermo (or optical) Luminescent Dosimeter (TLD) and the film badge, are used for legal records of individual exposure. The others are used for informational purposes only, to inform the wearer of the approximate dose that has been received or of the strength of the field that the worker is in.

TLD's

TLD's consist of small crystals, usually calcium fluoride, containing small amounts of impurities. Incident radiation excites atoms in the crystal which are "trapped" by these impurities. Upon heating (thermo-), the "trapped" excited electrons fall back to the ground state, giving up a photon (-luminescent) in the process. The number of photons released is proportional to the total radiation dose received. This photon signal is amplified by a photo-multiplier tube and the output sent to the dosimeter reader to register the dose.

TLD's have several advantages. They are extremely rugged and are not adversely affected by extremes in temperature. They are accurate over a very large exposure range - from mR to thousands of R. They are relatively quick and easy to read, allowing for speedy monitoring in emergency situations. They can be reused many times each, saving the expense of replacing them continually. And, finally, they are sensitive to beta, gamma, and x-ray radiation.

The disadvantages of TLD's over other methods of dosimetry are their higher initial cost and the fact that, once heated, the dose information is erased, unlike film badges, which can be reread if any questions arise at a later date.

Film Badges

Film badges make use of the fact that radiation, like light, will interact with silver halide crystals in film emulsion, causing them to darken. Also like light, the amount of the darkening is related to the total exposure. The film is placed in a holder that can also contain two or three shields of varying thicknesses, allowing measurement of skin dose as well as whole body (deep) dose. The film, once developed, is read by a densitometer to determine the overall dose that the wearer received.

The advantages of the film badge are its permanence, its cost, and the ability to allow simultaneous recording of exposure to different types or energies of radiation.

The disadvantages of film badges are the amount of time that it takes to develop and process the film, the sensitivity of the film to environmental factors such as temperature and humidity, and the fading that can occur if the film is not read promptly.
Film badges can be used to measure beta, gamma, and x-ray dose.

**Optically stimulated luminescent dosimeters**

OSL badges are similar to TLDs in their operating principles, except that they are read by scanning with a laser instead of being heated. The laser adds sufficient energy for the electrons to escape from their traps and, as with TLDs, they emit visible photons when they return to the ground state.

OSL badges are as sensitive as TLDs and, unlike TLDs, they can be read out multiple times because the laser can be set to scan only a part of the badge. This gives OSL badges the ability to be archived, as with film, for re-reading at a later time. Unlike film, OSL badges are not susceptible to environmental factors (at least, not to factors that are not fatal to the wearer). In many ways, these badges combine the best features of both film and TLDs with the exception of being more expensive than film. At present, OSL badges are offered by only one company.

**Self-Reading Dosimeter**

The self-reading dosimeter is basically a pocket ion chamber. It consists of two quartz fibers that can have a charge applied to them, acting as an electroscope. The end of one of the fibers is left free and is attached to a small hairline indicator that, as the dosimeter charges or discharges, is pulled across the indicating screen. As ionizations occur within the chamber the net charge on the fibers is lowered, causing them to draw together and pulling the hairline across the scale on the screen.

The advantages of these dosimeters is that they are relatively durable, provide a convenient way for personnel to monitor their dose while working, and can be produced to cover a very wide assortment of ranges. They are also, for the most part, energy-independent, allowing the counting of most gamma and x-ray radiation to which the wearer is exposed.

The self-reading dosimeters have several disadvantages, however. They can be easily discharged by dropping them or banging into something, causing them to go off-scale high and giving erroneous readings. Their orientation while reading them is also important; they may give very different readings depending on whether they are held right-side up or upside down due to the effects of gravity on what is primarily a mechanical system. They are also not extremely accurate, their accuracy depending upon the scale gradations, the initial zeroing accuracy, and the mechanical and electrical properties of the quartz fibers.

All in all, the self-reading dosimeters are not the best way to measure personal dose for a legal record. However, they are not designed to be. Their purpose is to provide personnel working in a radiation area the ability to roughly monitor their absorbed dose and they serve this purpose very well.
Audible Dosimetry (Rad-Tads, Chirpers)

These are small G-M tubes that give an audible chirp at intervals that reflect the strength of the radiation field. The faster they are chirping, the stronger the field is. They give no indication of total absorbed dose and are only an indication as to the radiation levels that the individual is in at the present time.
Dosimetry
Types of dosimetry

- Film badge
- Thermo-luminescent dosimeters (TLD)
- Optically-stimulated dosimeters (OSL)
- Neutron badges (various types)
- Electronic dosimeters
- Self-reading dosimeters (usually not used as dosimeter-of-record)
Film badge

- Radiation exposes film, so higher dose gives darker film
- Inexpensive, simple, cheap
- Oldest dosimetry technology
- Can be read multiple times
- However, can be sensitive to environment
- Lowest reading about 10 mrem
TLD

- Radiation exposure causes electrons to jump to higher stable energy level
- Heating crystal releases e\(^{-}\), photon emitted
- Rugged, accurate, mature technology
- Sensitive to wide range of energies
- Crystals can crack, can only be read once
- Lowest reading about 10 mrem
OSL

- Dose read by scanning with laser beam instead of heating
- Rugged, sensitive, can be re-read
- More expensive than other badges
- Sensitivity and performance sometimes erratic (personal observation)
- Only offered by Landauer
Neutron

• Variety of types
• Most are only sensitive to high OR low-
  energy neutrons, not both
• Need to know neutron energies in order to
  use correct badge

• Neutrons are hard to measure!
Electronic dosimeters

- Many designs
- Can be used in specific situations (e.g. entry into high radiation areas)
- Can also be used (sometimes) as dosimeter-of-record
- Can have interference from outside electrical signals
- Usually rugged and reliable
- Continuing to evolve at a rapid rate
Self-reading dosimeters

• Usually used only for entry into high radiation areas
• Usually used only for worker information
• Some recent models can be used as dosimeter-of-record
Dosimeter regulations

• Required for anyone expected to receive more than 125 mrem in a calendar quarter
• Required for anyone entering a radiation area or high radiation area
• In some cases, multiple dosimetry is required
  – Ring badges for people handling isotopes
  – Arm, collar, fetal, and other specialty badges as appropriate
Importance of dose records

- The single most important document to protect your company in the event of a radiation injury lawsuit is a set of dosimetry records showing that the worker did not exceed radiation exposure limits while working for your company.
- Dose records must be retained for 30 years after an employee leaves.
- May be asked to supply dose records to new employers for a departing employee.
Counting Statistics
Counting statistics

Not very exciting, but important anyhow
Basic terms

- Mean
- Mode
- Median
- Variance
- Standard Deviation
- Confidence Levels
Mean, median, and mode

- Mean - the arithmetic average of a collection of measurements.
- Mode - the most likely value in a set of measurements.
- Median - the center value in a set of measurements.

In a “normal” distribution, these are the same value.
Gaussian ("normal") distribution

- Centered around the mean
- Area beneath curve is equal to 1
- Asymptotically approaches X-axis
Some more terminology

• Accuracy – how close is the data to the “true” value?
• Precision – how closely clustered are individual measurements?
• Uncertainty – how much do the data vary from the “true” value.
• Error - commonly used in place of uncertainty
  – is more appropriate to indicate a mistake
Accuracy versus precision

- Accuracy
- Precision
Sampling a population

- Statistical methods attempt to infer information about an entire population from a sample of that population.
- Population - the entire group of possible measurements - population parameters are the true values.
- Sample - a small group of the population - sample parameters are the estimate of the true value made from the sample results.
Standard deviation

- Standard Deviation – a measure of the variability in the data.
- Mathematically noted as multiples of $\sigma$
  - 65% of members of a population fall within the 1 $\sigma$ error bars
  - 95% fall within the 2 $\sigma$ error bars
  - 99% fall within the 3 $\sigma$ error bars
- So, if a paper reports results to the 95% confidence interval, they are reporting results to the 2 $\sigma$ level
### Sample Calculation

**NORMAL DISTRIBUTION**

The mean is the sum of the data divided by the number of measurements (N).

<table>
<thead>
<tr>
<th>Data</th>
<th>Deviation</th>
<th>Deviation^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>23</td>
<td>-3.95</td>
<td>15.6025</td>
</tr>
<tr>
<td>24</td>
<td>-1.95</td>
<td>3.8025</td>
</tr>
<tr>
<td>27</td>
<td>0.05</td>
<td>0.0025</td>
</tr>
<tr>
<td>24</td>
<td>-9.95</td>
<td>9.3025</td>
</tr>
<tr>
<td>26</td>
<td>-0.95</td>
<td>0.9025</td>
</tr>
<tr>
<td>28</td>
<td>1.05</td>
<td>1.0025</td>
</tr>
<tr>
<td>26</td>
<td>-0.95</td>
<td>0.9025</td>
</tr>
<tr>
<td>25</td>
<td>-1.95</td>
<td>3.8025</td>
</tr>
<tr>
<td>28</td>
<td>1.05</td>
<td>1.1025</td>
</tr>
<tr>
<td>33</td>
<td>6.05</td>
<td>36.6025</td>
</tr>
<tr>
<td>31</td>
<td>4.05</td>
<td>16.4025</td>
</tr>
<tr>
<td>19</td>
<td>-7.95</td>
<td>63.2025</td>
</tr>
<tr>
<td>23</td>
<td>-3.95</td>
<td>15.6025</td>
</tr>
<tr>
<td>26</td>
<td>-0.95</td>
<td>0.9025</td>
</tr>
<tr>
<td>28</td>
<td>1.05</td>
<td>1.1025</td>
</tr>
<tr>
<td>26</td>
<td>-0.95</td>
<td>0.9025</td>
</tr>
<tr>
<td>29</td>
<td>2.05</td>
<td>4.2025</td>
</tr>
<tr>
<td>31</td>
<td>4.05</td>
<td>16.4025</td>
</tr>
<tr>
<td>COUNT</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>SUM OF SQUARES/(N-1)</td>
<td>12.6815789</td>
<td></td>
</tr>
<tr>
<td>MEAN</td>
<td>26.95</td>
<td></td>
</tr>
<tr>
<td>STANDARD DEVIATION</td>
<td>3.5611</td>
<td></td>
</tr>
<tr>
<td>VARIANCE</td>
<td>12.682</td>
<td></td>
</tr>
</tbody>
</table>
Choosing counting times

- Good counting statistics require many total counts, but this can require long counting times
- Time constraints may lead to poor counting statistics
- Need to optimize counting times to make best use of existing time
- Longer counting times give better stats, but the advantage gained drops off (i.e. a 10 minute count is not 10 times better than a 1 minute count)
- The goal is to achieve good counting stats in the shortest time
Effects of background

- Background radiation levels (or count rates) change continuously and randomly.
- Need to make sure that elevated counts are really due to contamination and not to random fluctuations in background.
- Can either perform multiple background counts (and average them) or a single, long background.
**Effect of Background on Statistical Parameters**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_g$</td>
<td>100 cpm</td>
</tr>
<tr>
<td>$R_b$</td>
<td>20 cpm</td>
</tr>
<tr>
<td>$R_n$</td>
<td>80 cpm</td>
</tr>
<tr>
<td>$t_g$</td>
<td>2 minutes</td>
</tr>
<tr>
<td>$t_b$</td>
<td>2 minutes</td>
</tr>
</tbody>
</table>

$S_{net} = 7.745967$

Net count rate = $80 \pm 7.745967$ (1 sigma limits)

Change count time for background to 20 minutes:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_g$</td>
<td>100 cpm</td>
</tr>
<tr>
<td>$R_b$</td>
<td>20 cpm</td>
</tr>
<tr>
<td>$R_n$</td>
<td>80 cpm</td>
</tr>
<tr>
<td>$t_g$</td>
<td>2 minutes</td>
</tr>
<tr>
<td>$t_b$</td>
<td>20 minutes</td>
</tr>
</tbody>
</table>

$S_{net} = 7.141428$

Net count rate = $80 \pm 7.141428$ (1 sigma limits)
Optimum Use of Counting Time

Provides the ratio of the sample count time to the background count time that results in the smallest standard deviation.

- Time available to count: 30 minutes
- Typical sample count rate: 100 cpm
- Typical background count rate: 20 cpm

\[ \frac{t_g}{t_b} = 2.236068 \]

\[ t_b + 2.236067977 * t_b = 30 \text{ minutes} \]

\[ 3.236068 * t_b = 30 \text{ minutes} \]

- Background count time = 9.27051 minutes
- Sample count time = 20.72949 minutes

\[ \frac{T_s}{T_{b, opt}} = \sqrt{\frac{G}{B}} \quad \frac{T_s}{T_{b, opt}} = \sqrt{\frac{80 + 20}{20}} = \sqrt{5} = 2.236 \]
Effect of changing counting times

- In general, the 1σ level is equal to the square root of the total counts.
- If background count rate is about 100 cpm, we have the following 1σ levels.

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Total counts</th>
<th>1 σ counts</th>
<th>1 σ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>50</td>
<td>7.1</td>
<td>14.1</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>14.1</td>
<td>7.1</td>
</tr>
<tr>
<td>10</td>
<td>1000</td>
<td>31.6</td>
<td>3.2</td>
</tr>
</tbody>
</table>
Confidence levels

- Confidence levels or probability factors have been identified for the normal distribution.
- The confidence value is an estimate or prediction of what percentage of the measurements are expected to be within a range of values.
- Commonly called “k” values, 1 σ is 68%, 1.65 refers to 90% CL, and 1.96 for 95%.
Utility of Confidence Levels

- Allow prediction of the Lower Limit of Detection, Minimum Detectable Activity, Critical Level, Limits for Control Charts, etc.
- Since they are an estimate of the limits, and the normal distribution curve only approaches the horizontal axis, some population values can always fall outside a calculated range. The “k” value can be used to estimate, or minimize that probability.
Decision level

- When a sample does not contain activity, the net count rate should be zero. Although the mean net count rate is zero, the distribution of count rates in a population may contain some positive and negative values.
- The Decision Level is a derived value that the count or count rate must exceed to conclude that activity is really present.
  - Reduces the risk that random fluctuations in background will masquerade as contamination.
Some definitions (from MARSSIM)

- **The critical level (LC)** is the level, in counts, at which there is a statistical probability (with a predetermined confidence) of incorrectly identifying a measurement system background value as “greater than background.” Any response above this level is considered to be greater than background.

- **The detection limit (LD)** is an a priori estimate of the detection capability of a measurement system, and is also reported in units of counts.

- **The minimum detectable concentration (MDC)** is the detection limit (counts) multiplied by an appropriate conversion factor to give units consistent with a site guideline, such as Bq/kg.
LC = k × \sqrt{\frac{R_b}{t_b} + \frac{R_b}{t_s}}

- LC is the decision level
- k is a factor related to the confidence level - when k=1.645 the confidence level is 95%, when k=1.96 the confidence level is 99%.
- R_b is the background count rate.
- t_b is the background count time.
- t_s is the sample count time.
Minimum Detectable Activity

- MDA is the lowest activity level that can be detected with a given degree of certainty.
- MDA depends on background level, detector efficiency for the nuclide in question, and the desired level of precision.
- Also called Minimum Detectable Concentration (MDC).
Field surveys – minimum detectable count rate

• The MDCR is the lowest number of counts above background that you can confidently claim indicates actual contamination and not a random fluctuation in background counts
\[ s_i = d \sqrt{b_i} \]

- \( s \) is the minimum number of net source counts in a given counting interval (i.e. the lowest number of counts you can detect)
- \( d \) is from the table on the following slide
- \( b \) is the number of background counts in a given counting interval
### False positive probability (MARSSIM)

**Table 6.5 Values of \( d' \) for Selected True Positive and False Positive Proportions**

<table>
<thead>
<tr>
<th>False Positive Proportion</th>
<th>0.05</th>
<th>0.10</th>
<th>0.15</th>
<th>0.20</th>
<th>0.25</th>
<th>0.30</th>
<th>0.35</th>
<th>0.40</th>
<th>0.45</th>
<th>0.50</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>1.90</td>
<td>1.94</td>
<td>1.98</td>
<td>2.02</td>
<td>2.06</td>
<td>2.11</td>
<td>2.15</td>
<td>2.20</td>
<td>2.25</td>
<td>2.30</td>
</tr>
<tr>
<td>0.05</td>
<td>2.04</td>
<td>2.08</td>
<td>2.12</td>
<td>2.17</td>
<td>2.22</td>
<td>2.27</td>
<td>2.32</td>
<td>2.38</td>
<td>2.43</td>
<td>2.48</td>
</tr>
<tr>
<td>0.10</td>
<td>2.16</td>
<td>2.21</td>
<td>2.26</td>
<td>2.32</td>
<td>2.38</td>
<td>2.44</td>
<td>2.50</td>
<td>2.57</td>
<td>2.63</td>
<td>2.69</td>
</tr>
<tr>
<td>0.15</td>
<td>2.32</td>
<td>2.38</td>
<td>2.44</td>
<td>2.51</td>
<td>2.57</td>
<td>2.64</td>
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105
### MDCR table

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<tr>
<th>Background (cpm)</th>
<th>MDCR (net cpm)</th>
<th>Scan Sensitivity (gross cpm)</th>
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<tr>
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*The sensitivity of the ideal observer during the first scanning stage is based on an index of sensitivity (I) of 1.38 and a 2-second observation interval.*
Example calculation

- So, if background count rate is 1500 cpm and you assume that a given area will be under the probe for about 1 second, the background count rate (b) for any given area is about 25 counts per second.

- If you decide to allow up to 60% false positive rate and a 95% confidence interval, d’=1.38 and s_i=414 cpm above background (for a total of 1914 cpm).
Control charts

- Used to identify instrument trends, even before an instrument goes "out of specification"
- Obtain a number of sample counts for a source and background.
- Determine the mean and standard deviation of both sets of data.
- Plot daily or weekly checks against mean and pre-determined error bars and examine for trends
Expected response – variations around the mean
Possible problem – dropping trend in beta readings

Beta Source Response Control Chart

- Beta Response
- ±10%
- Average

Date: 6/8/2001 to 7/18/2001

Beta Source Response (cpm)

3500 3600 3700 3800 3900 4000 4100 4200 4300 4400 4500

______________________________________________________________________

______________________________________________________________________

______________________________________________________________________

______________________________________________________________________

______________________________________________________________________

______________________________________________________________________

______________________________________________________________________
Case study #1

• In a remediation plan, one licensee claimed a pile of soil was well-characterized and could be released for disposal
  – The release limit was 35 pCi/g
  – Ave. contamination levels were 33 pCi/g
  – Standard deviation was 34.5 pCi/g
• Should the licensee’s claim be believed?
Case study #2

- A licensee’s I-131 emissions suddenly skyrocketed, leading to cessation of I-131 use for several months. However, 3 months after use stopped, I-131 was still counted in the sample filters.
- The reason for this is that, with 1-minute sample and background counts, random fluctuations in background showed up as “real” counts and, subsequently, as discharges.
- Solution was to increase counting times and to use a single-channel analyzer to reduce background counts in energy regions of interest.
## Case study #2 data

<table>
<thead>
<tr>
<th>Trial</th>
<th>1 minute background counts</th>
<th>10 minute background counts</th>
<th>Count Rate</th>
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<td>407</td>
<td>435</td>
<td>407</td>
</tr>
<tr>
<td>2</td>
<td>432</td>
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<td>3</td>
<td>407</td>
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<tr>
<td>4</td>
<td>414</td>
<td>431</td>
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<td>5</td>
<td>428</td>
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<td>6</td>
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<tr>
<td>11</td>
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### Descriptive statistics

<table>
<thead>
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<th></th>
<th>1 minute dataset</th>
<th>10 minute dataset</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
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<td>439.9500</td>
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<tr>
<td>Median</td>
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<td>Mode</td>
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<tr>
<td>Standard Deviation</td>
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<tr>
<td>Sample Variance</td>
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<tr>
<td>Confidence Level 95%</td>
<td>12.9444</td>
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Instrument calibration
Instrument calibration
Instrument calibration

- Instruments must be calibrated annually, after repairs, or when the fail daily performance checks
- You can calibrate instruments in-house or send them out for calibration
- May also perform regular checks of instrument performance
Purpose of calibration

• Verify instruments function properly
• Perform adjustments necessary to meet performance goals or requirements
• Confirm instrument was working properly (during a closeout survey, for example)
If you don't calibrate your meters:

- Limited ability to relate readings from different areas.
- Limited ability to compare readings between instruments.
- Inconsistent response for the same radiation fields but of different intensity.
- Limited ability to accurately repeat readings
Calibration record-keeping

- Measurements of radiation are made to protect personnel and establish proof or compliance with regulations.
- It is essential to provide a solid path of accurate calibration on paper to prove that instrumentation is calibrated and maintained appropriately.
Performance checks

• Performance checks are evaluations carried out periodically to evaluate acceptable instrument response for an intended use.
• Performance checks should validate that the instrument has maintained its calibration for a specific purpose.
• Example: daily instrument response checks
Checks to be conducted before each use

- Verify the battery condition is adequate
- Verify audible response when needed
- Verify acceptable response to a source of known strength (± 20%)
- Verify background radiation levels
- Check physical condition of instrument
- Should be documented with a verification signature by the user that the instrument is operating properly.
Conducting calibrations

- Dose rate instruments are calibrated in a radiation field of known strength.
- Count rate instruments are calibrated with an electronic pulser, and low-activity check sources can be used to check meter efficiency.
- Integrating dose instruments are calibrated by exposing them to a known radiation field for a given period of time.
Other considerations

- Temperature and humidity (especially for air ionization chambers)
- Geotropism (not applicable to digital meters)
- Wall thickness (thick-walled meters are less sensitive to low-energy radiation)
- Chamber size vs. beam size (need to irradiate entire ionization chamber)
- Mixed radiation fields may interfere with readings
Routine calibrations

- NCRP 112 says that routine calibration should:
- Include the types, energies, and intensities of radiation that the instrument was designed for and within those parameters, for which it is being used to measure.
- Be performed with the detector and instrument in the correct operating position.
- Not subject the instrument to undue mechanical stress.
- Be conducted in the environmental conditions for which the instrument was designed.
Routine calibrations

- Are often limited to the determination of reading linearity in response to a single radiation type of a specified energy.
- Depending on the use of the instrument, such a calibration may not provide the expected accuracy to the user.
  - For example, some users must monitor different types and energies of radiation (e.g. I-131, Tc-99m, Co-60)

- Ask for what you need or you won’t get it!
Dose rate versus count rate calibrations

- There is a tendency to calibrate instruments inappropriately (e.g. calibrating GM pancake probes for dose rate AND count rate)
- It is important to calibrate instruments for their designed use and to account for their limitations
Other calibration considerations

- Radiation type (α, β, γ)
- Radiation field intensity
- Source to detector geometry
- Source geometry (point, distributed source)
- Uniformity, angular response, source to detector distance
- Traceability of sources
- Accuracy of instrument
- Incidental or spurious radiations (including scatter from calibration source or range)
Calibration source strength

- In order to provide calibration over several different measurement ranges from micro-rem/hour to hundreds of rem/hour it may be necessary to have multiple calibration sources of activity from microcuries to several curies.
- Large sources will require licensing
NIST traceability

- All sources used in calibration should be traceable to NIST primary standards
- NIST verified calibration standards can be obtained by:
  - Sending sources to NIST for calibration
  - Sending instruments to NIST for calibration
  - Purchasing NIST calibrated sources
Radiation energy dependence

• Most instruments and detectors exhibit their greatest energy dependence at low energies
  – < 200 keV for photons,
  – < 500 keV for beta particles,
  – < MeV for neutrons.
  – At these energies the instruments will over respond by factors of 2 to 15.
• Need to understand energy of radiation to be measured to calibrate dose-rate instruments properly
Calibration range setup

- The detector must be far enough away from the source to appear to be a point source (makes calculations accurate)
- Accuracy is best when the distance from the source to the detector center is at least five times the detector diameter.
- Dose rate detector must be completely and uniformly exposed to radiation field
Calibration facility considerations

• Design of the equipment and facility.
• Layout of the calibration process in the facility.
• Qualifications and capabilities of personnel.
• Supervisor review of calibration and documents.
• Management qualifications and observation of the process periodically.
• QA Evaluation by impartial observers.
• Inter-laboratory comparison checks.
Background Radiation

- Should be reduced to as low a level as reasonable
- It must be below the level at which it would interfere with the calibration process.
- Less than 1% of the value being used to calibrate the instrument is generally acceptable.
- The facility should be located remote from known spurious sources of radiation to not only minimize background, but also to ensure stability in the background measurements.
Scattered Radiation

- Is of concern in any calibration for gamma, neutron, and beta radiation.
- Gamma radiation scatters most significantly in high atomic number (Z) material.
- Neutrons scatter most significantly in low atomic number material (Hydrogen).
- Beta radiation in addition to scatter (backscatter) will cause x-rays in high Z material.
- Calibration ranges are typically large rooms with open air around the location of the instrument.
Scattered Radiation

- If a range track is used to hold the instrument, materials should be low Z such as aluminum, carbon
- The shielding of calibration sources should be such that the emissions from the shield do not affect background measurements
- Beta sources have many scattering considerations such as air scatter, backscatter, scattering in support equipment, attenuation in covering materials, etc. All of these may significantly affect the result of a calibration
Calibration equipment:

- Should be designed to minimize effects of:
  - background radiation,
  - scattered radiation,
  - environmental effects
  - provide radiation protection for workers.
- This may include:
  - remote control of sources,
  - source interlocks,
  - audible and visual alarms indicating source exposure,
  - radiation monitoring during exposure,
  - collimators, accurate timing devices, accurate distance measuring devices,
  - cameras, mirrors, support devices of low Z material, good room shielding, environmental monitoring, etc.
Environmental Conditions

- Temperature should be between 18 and 27 C (65 and 80 F).
- Relative Humidity should be 10 - 70%
- The facility should be kept clean with intake and exhaust ventilation filtration.
- The facility should be remote from electromagnetic influences such as high voltage transformers, power lines, and arc welding equipment.
Scattered radiation

- Alpha and beta radiation can scatter back from hard surface, increasing the measured count rates
- Gamma radiation can scatter from walls, floor, or ceiling of small calibration range, increasing measured rad levels
- Need to design calibration facility to minimize or account for scatter
Linearity checks

- Evaluation of linearity should be made on each range that the instrument is used.
- Obtain at least two readings separated by 40% on each scale and equidistant from the scale center,
  - Typically done at 30% and 70% of full scale
- For analog instruments with multiple-decade log-scale displays and for digital instruments with no scale selection, at least one point in each response decade should be used in the calibration. For these displays, the end of the decade may be easier to read
- Must be ±20% of expected reading (anything greater than ±10% requires noting a correction factor
Count rate calibrations

- Use electronic pulser to perform calibration
  - Pulser must be calibrated periodically
- May still need to determine counting efficiency for various energies, using small check sources
- Example: a count rate of 100,000 cpm on a 0.1 µCi source has an efficiency of 45%
Counting efficiency

- When performing a contamination survey, it’s important to know the relationship between counts detected by the meter and amount of contamination (DPM) present on the surface.
- During calibration of count-rate instruments, should determine counting efficiency for primary isotopes in use.
Example counting efficiencies

- P-32, GM pancake probe, about 35-40%
- P-32, 1"x1mm NaI, about 35-40%
  - Why (P-32 is a beta emitter)?
- C-14, S-35, GM pancake, about 3-5%
- I-125, thin xtal NaI, about 10%
- I-125, thin xtal NaI, neck phantom, ~1%
- H-3, Liquid scintillation counter, ~50%
Example

- What is the counting efficiency when you measure 80K cpm on a 0.1 μCi P-32 source?

\[
0.1 \mu Ci = 2.22 \times 10^5 \text{ dpm}
\]

\[
\frac{80,000}{2.22 \times 10^5} = 36\%
\]
Example 2

• You are calibrating a 1"x1" NaI detector for Cr-51 using a 0.1 µCi Ba-133 check source and you are reading about 60,000 cpm. What is the counting efficiency for Cr-51?
• In this problem, it’s important to understand that the Cr-51 gamma is emitted with only one sixth the probability as the Ba-133 gamma. Therefore, when you calculate the Cr-51 counting efficiency, you must first calculate the Ba-133 counting efficiency and then divide by 6
Solution

\[
\frac{6000}{2.22 \times 10^5} = 2.7\% \\
\frac{2.7\%}{6} = 0.45\%
\]
Records to keep

- Internal records that must be maintained:
  - Traceability of Radioactive Standards
  - Traceability of Electronic Standards
  - Calibration documents of instruments used to make measurements on instruments.
  - Dates that instruments were received and the initial condition of those instruments.
  - Training and qualifications of personnel doing the calibration.
More records

- Calibration documents should clearly specify:
- Calibration data including:
  - Instrument model and serial number
  - Instrument manufacturer
  - Date of calibration and due date for next calibration
  - Identification and calibration dates of instruments used.
  - "As found" measurements.
  - Limitations of the calibration.
  - Special calibration considerations.
  - An estimate of calibration uncertainty
References:

• ICRU 47
• NCRP 112
• ANSI N42.17A-1989
• ANSI N323-1978 (R1993)
• NIST - NBS SP 250, NBS 250-16.
• ICRP 21, 26, 35, 51, 60
• ICRU 25, 33, 34, 40, 43
• NCRP 57, 58, 82, 116
Air sampling
Air sampling

A case study, from a consulting client.

Investigation into elevated I-131 emissions
I was informed by the facility manager and RSO that, in the last few months, emissions of I-131 have increased significantly, and I was asked to investigate this increase. I first confirmed that the elevated readings appear to be “real” and not computational errors. I am satisfied that the calculated numbers are not the result of computational error, but it is possible that the effluent sampling system in use may be contributing to the manner in which readings have changed with time. This, and other relevant issues are described in more detail below.

History
On April 7, 2003 this facility began using a new formulation of I-131 NaI that is designed to be less volatile in liquid form than the previous formulation. Unfortunately, it appears as though, when dry, the new formulation may be more volatile, so the routine splatters or spills that are an unavoidable part of working with isotope became more significant in terms of contributing airborne radioactivity. The fact that the new formulation also contains a higher activity concentration than did the previous formulation has exacerbated this problem.

At about the same time, this facility began using different syringes (for transferring isotopes to unit dose vials) that could be used multiple times. The longer syringe became a concern because it was more prone to vibration, “flicking” small droplets into the fume hood when withdrawn from the vials of I-131 solution. In addition, storing syringes for reuse gives the contamination a longer time in which to evaporate and enter the effluent airstream. Here again, the higher activity concentration would give each small droplet a higher impact on airborne emissions.

On May 29, 2003, some changes were made to the air sampling system that included installation of a new anemometer. The increased effluent activity levels were noted almost immediately following this work.

The facility RSO and manager took several actions to attempt to reduce airborne emissions. These actions included:

1. Fume hood decontamination
2. Sealing off fume hood from rest of lab
3. Relinquishing I-131 work to another corporate facility
4. Modifying use and storage of reusable syringes

As noted on the attached charts, measured airborne emissions levels began increasing significantly about one month after making these changes, and have remained high since that time. As a result, this facility has emitted more I-131 than is allowed by ___
permit, although they remain within the legal average effluent activity limits \((2 \times 10^{-10} \mu \text{Ci/ml})\) specified by state and federal regulations.

**Investigation**

I began by entering air sampling data from Jan 7, 2003 until the present. Some of the data entry was designed to double-check the computed air flow and activity emissions information produced by the facility computer system (the RS-55 form), and the balance was to permit analysis of this data. The sample calculational checks indicate that the software is calculating correctly\(^1\). The charts that were produced are attached.

These data strongly support an increase in air sample activity beginning during the week of May 6 and continuing until the present. According to the data, the first two weeks saw a mild increase in airborne emissions followed by a more dramatic rise beginning in late May and continuing until the present. There are two notable facts about the timing of these emissions:

1. There was a time lag of about 1 month before emissions began to increase
2. In spite of no use of I-131 since June 23(?) samples taken in the last week are among the highest to date\(^2\).
3. Smear wipes taken on June 30 indicate there is no contamination present on the sides of the exhaust stack.
4. Other smear wipes taken of the inside of the sample tubing show low levels of contamination, as do smear wipes taken in the fume hood exhaust ducting. However, radiation levels of about 5 mr/hr were measured in the charcoal exhaust filters located on the facility roof.
5. The data show that radioactivity concentrations in samples of “unrestricted” air (i.e. from the filtered exhaust) were about the same as those from the “restricted” (i.e. in the room) air until early May, when the unrestricted air effluent concentrations rose significantly. This differential became even more marked after the week of May 27, 2003 and has continued, with only a few exceptions, since that time.

The first two facts suggest that, in addition to problems caused by the new formulation of iodine and the use of reusable syringes, there may be systematic effects at work that are introducing a delay between changing practices and measured activity in fume hood effluent. The third, fourth, and fifth suggest these elevated readings may be an artifact of the sampling system. This will be discussed in more detail later in this report.

**Regulatory compliance issues**

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\(^1\) However, the facility RSO and manager have noted that the cumulative emitted activity calculation corporate software does not appear to update automatically every time new data are input but, rather, seems to update this value only weekly. This makes “real-time” tracking of emitted activity difficult.

\(^2\) When viewing the charts, one must remember that sampling frequency was weekly at first, increasing to twice weekly in mid-June and daily in late June. Therefore, the last several values shown should be added together to allow accurate comparison with earlier emissions.
In accordance with its DEC permit, this facility is allowed to emit 630 µCi of I-131 annually. The calculated emissions thus far this year (in excess of 900 µCi) are in excess of this permit limit.

The limit for average annual airborne concentrations for I-131 is $2 \times 10^{-10}$ µCi/ml. As of June 30, 2003, the calculated average effluent airborne concentration of I-131 is $1.44 \times 10^{-10}$ µCi; less than the regulatory limit, but uncomfortably close. In addition, if current trends continue, the regulatory limit will be exceeded before the year ends.

Accordingly, at least two actions are required if these values are found to be correct:

1. Request an amendment to the facility’s DEC permit to allow emission of more than 630 µCi of I-131 in this (and subsequent) calendar years.
2. Correct the root causes for these elevated readings.

**Air sampling system, fume hood exhaust system**

The facility RSO and I performed some radiological testing on the fume hood exhaust system. No smear wipes from anywhere in the system showed elevated levels of radioactivity, suggesting the fume hood exhaust is “clean”. Radiation monitoring on the charcoal exhaust filters indicated levels of 5 mR/hr with a NaI micro-R meter. This indicates that radioactive materials were entrained in the fume hood exhaust, were trapped by the filter, and failed to contaminate any part of the fume hood exhaust ductwork. This also suggests that contamination measurements of the fume hood exhaust ducts cannot be used to indicate the use of iodine. Accordingly, it is still not possible to say definitively whether or not I-131 measurements are “real” or, instead, are an artifact of the sampling system.

The air sample line runs from the fume hood exhaust (downstream of air filters) through the ceiling and above the ceiling across two rooms (about 10 meters) before descending to the sample point in the iodine room. The long horizontal segment could allow for the collection of iodine or iodine-bearing particulates, although radiation monitoring was inconclusive.

As noted in an earlier report, some parts of this facility’s air sampling system are not in agreement with the recommendations of the American National Standards Institute (ANSI) as outlined in their report ANSI/HPS N13.1 (1999). In particular, the air flow velocity through the sampling tube is lower than in the exhaust stack and the sample line is not heated.

If flow velocity is slower in the sampling tube than in the exhaust stack, particulates or small droplets entrained in the main airflow can settle out in the sample tube and be removed from the bulk air being sampled. Due to its chemical reactivity, iodine vapors may react with small particles in the air, either forming chemical bonds with the particles or adsorbing onto their surfaces. In either case, the iodine will then move in particulate form rather than as a vapor.
they accumulate to the point of being swept up in the airstream passing through the tube. In both cases, activity may accumulate in low-flow parts of the sample tubing. This would result in a time lag between when activity is emitted from the stack and when it is detected by the sample filter. During this time lag, some radioactive decay will occur, and it is possible that the actual activity emitted will exceed what is calculated.

The ANSI also notes that volatile compounds such as iodine will tend to condense on the surface of a cool tube and, as a result, they will be removed from the sampled air. This, again, will tend to reduce the amount of radioactivity on the filter and will yield erroneously low sample results.

It is also possible that the sample system is contaminated or that recent changes to the sample system may be contributing to the recent elevated readings. For example, re-routing the sample tube may lead to exposing previously low-flow sections of the sample tube to higher-velocity airflow, while handling the tube could free activity previously stuck to the tubing walls. The latter action would lead to a prompt increase in measured activity followed by a drop in the following week while the former may lead to a longer-term increase in measured activity, gradually dropping as the attached particles or droplets were swept away.

**Data interpretation**

The data seem to suggest that both work practices and the sampling system are responsible for the noted increase in I-131 emissions. Looking at the data for calculated activity emissions, the first 13 weeks of this year had three occasions in which emissions exceeded 5 µCi, while the next 13 weeks had 10 instances in which this level of emissions was exceeded. The 13th week of the year was the week of April 1.

However, there is no dramatic increase in effluent activity until the week of May 27, 2003, and 9 of the 10 highest effluent calculations occur after this time. This strongly suggests that the work done on the air sampling system is also responsible for the recent increases in airborne effluents. However, further investigations will be required to determine what happened, how it can be corrected, and whether or not the recent effluent concentrations are or are not an accurate reflection of actual effluent levels.

**Possible explanations**

There are several possible explanations for the apparent high effluent iodine emissions that have been noted:

1. The readings may reflect actual emissions
2. Contamination within the sample lines may be causing elevated readings
3. An isotope other than I-131 may be present in the air
4. The sampler filters may be radioactively contaminated
5. The sample line may be leaking inside the iodine room, allowing air from the restricted area to enter the filter
**Recommendations**

It is necessary to determine:

1. If the isotope present on the air sample filters is I-131 or another gamma-emitting nuclide
2. If the elevated levels of isotope measured are representative of levels in the airstream or if they are an artifact of the sampling system
3. If the sampling system is somehow contaminated

Accordingly, I recommend taking the following actions to resolve the origin and legitimacy of the elevated air sample readings:

1. Perform a nuclide ID on at least one air sample filter to confirm the gamma energy is consistent with I-131. If the nuclide is not I-131, identify the nuclide and determine allowable emissions concentrations.
2. Inspect the sample lines, particularly those inside the iodine room, for leaks to determine if leakage from the restricted area into sample lines from the unrestricted area may be causing problems.
3. Count a blank sample filter to check for contamination in the filter media and/or the gamma counter.
4. Draw an air sample in the rooms adjacent to the iodine rooms through which the unrestricted sample line runs. This may help to determine whether or not airborne isotopes in these rooms may be contaminating the filter.
5. If high readings persist, you may consider replacing some or all of the sample tubing from the unrestricted area and/or fittings and sample cartridge in case the elevated readings come from contamination in the sampling lines.
6. You may also consider removing the sample tubing and flushing with warm, soapy water or a cleaning solution to remove any contamination that may be present.
7. Regardless of the origin of the elevated readings, I recommend re-routing the sample line to minimize its length and the number of flat or nearly flat stretches of line. Ideally, the sample line should descend as vertically as possible from the sample point to the sample filter. This would mean locating the filter in the room directly beneath the exhaust stack, although the pump may remain in its current location.

Hopefully, the above measures will help to resolve the “reality” and origin of the elevated readings. If the readings persist and continue to be inexplicable, further investigation will be necessary.

Finally, I recommend the following actions be taken regarding regulatory compliance matters and work practices:

1. Verbally notify DEC of elevated readings, actions taken to date, and current thoughts (i.e. the readings may be real or may reflect sampling problems). Request time to resolve these issues before submitting either a permit amendment application or a formal written report.
2. If necessary, request appropriate discharge limit modifications in the facility permit.
3. Modify work practices to minimize the re-use of contaminated equipment (e.g. syringes)
4. Modify work practices as necessary to minimize the chance of spreading contamination in the fume hood. This may include using shorter syringes, using a small pump to dispense iodine instead of a syringe, replacing absorbent materials in the fume hood immediately after handling iodine, working inside a mini hood located inside the fume hood, using a charcoal filter on top of the vial when initially opening it to trap vapors, or other means of controlling emissions that have been found to be successful in other corporate facilities.
5. Consider returning to the prior formulation for I-131 NaI.

Follow-up #1: the next month
Last month’s report focused on a dramatic increase in airborne emissions of I-131 since April of this year. In the past month, ______ has discontinued use of the longer syringe that seemed implicated in “flicking” drops of I-131 solution and increasing contamination levels in the fume hoods. This facility continued having I-131 compounded at the Syracuse facility, and embarked on an extensive cleaning of their fume hood. In the past month, I-131 emissions seem to have peaked and are now decreasing, although it is not precisely known that this drop is due to the measures taken or to other factors. They have been below allowable release levels (% effluent limits) since July 5, 2003.

According to telephone conversations with the NY DEC, the elevated releases will likely be considered an incident and will not be counted towards this facility’s allowable releases for this calendar year. This decision followed extensive telephone and written communications between ____ and the DEC, along with evidence that many other corporate facilities have experienced similar increases in airborne emissions due to the new I-131 formulations and equipment changes, as noted in a memo dated June 23, 2003.

In addition, the facility manager is investigating the possibility that the existing charcoal filters are inadequate for the task of filtering I-131 from the air exhaust. He notes that the existing filters were not designed by engineers, they do not meet accepted nuclear industry standards, the charcoal is present as pellets and not granules (with concomitantly lower surface area), and the charcoal is prone to settling with time. He feels that changing to a properly designed filter system that contains a greater thickness of charcoal granules, fewer gaps, a HEPA pre-filter, and other improvements will greatly reduce airborne emissions; and he notes that such filters are used successfully in other companies working with large quantities of I-131. Also mentioned was the possibility that reducing fume hood exhaust flow rates would result in longer residence time of air in contact with the charcoal filters, improving adsorption (this would also lessen the degree of anisotropy in the sample line flow) and reducing emissions. I concur with this assessment, but I also note that there have been a number of changes in recent months
and it is not certain which of these changes is responsible for both the rise and the subsequent drop in I-131 emissions. Accordingly, I strongly recommend continuing to closely track I-131 emissions as the new filter assembly is installed and as the revised practices are used. If I-131 emissions do not drop as quickly or as much as expected, I think there would be value in positively identifying the isotopes present in the sample filters and, if necessary, inspecting the sampling system for leaks or design improvements.

Follow-up 2: Two months later

As indicated in previous reports, there have been some problems noted regarding higher-than-expected emissions of I-131 from this facility. Possible sources of these elevated emissions have been suggested:

1. Use of Hamilton syringe, which can cause higher levels of contamination inside the iodine fume hood
2. Use of new high-activity formulation of I-131 NaI
3. Inefficient filter design that allows unfiltered air to bypass the filter cartridges

In addition, some aspects of the air sampling system have been identified that may result in air samples that are not representative of effluent air:

1. Anisokinetic air flow in sample lines
2. A large distance of sample tubing between the sample point and the sample filter
3. Unheated sample tubing that may permit iodine condensation in the tubing

Finally, there are some other possibilities that could lead to erroneous elevated sample readings:

1. Presence of other isotopes (e.g. Tc-99m, radon progeny) in the sample tubing
2. Change in sample line configuration, leading to release of condensed iodine into the sample filter
3. Attempting to attribute activity to samples that is actually due to random fluctuations in background count rate

In the time since this problem was first noted, the following steps have been taken, with the noted results:

1. The fume hood has been extensively decontaminated on multiple occasions.
2. Exhaust filters have been changed several times.
3. This facility has stopped using the Hamilton syringe and, ultimately, stopped compounding iodine doses
4. Nonetheless, iodine emissions continue to be elevated, albeit at lower levels than when this issue first became a concern.
   a. This last item is surprising, because iodine has not been compounded at this facility in 67 days (as of the date of this visit) – over 8 half-lives. Given
that the current airborne concentrations of I-131 are noted as being comparable to those measured earlier this year, when compounding was still taking place (and before changing to the Hamilton syringe and the new formulation), it seems possible that there is a problem with the counting system, leakage into the sample system, that long-lived isotopes are present, that radon progeny are being counted, or that the count rates noted are actually too low to quantify.

b. One sample filter was re-counted after one week and was found to have a net count rate of zero (compared to 102 cpm above background when drawn). A Co-57 source was counted and had moderately elevated counts, although not statistically significant. These two observations suggest that the scalar energy window is operating properly and that lower-energy isotopes (e.g. Tc-99m) are not interfering with sample counting.

c. Further checks indicate that 1-minute background count rates varied from 407 to 462 cpm, and the 10-minute background counts varied from 437 to 458 cpm. The exact count rates are recorded in the attached table.

d. Given the above, counting statistics suggest that, with a 1-minute sample and background counting time, the MDA is 1254 counts and the detection limit is 100 cpm above background (using the detector efficiency noted on the sample form). Extending the background count rate to 10 minutes and retaining a 1-minute sample counting time lowers the MDA to 939 cpm above background with a detection limit of 75 cpm above background. Counting both sample and background for 10 minutes results in an MDA of 389 and a detection limit of 31 cpm above background.

e. It is possible, indeed likely, that counting statistics (including random fluctuations in background radiation levels) are a contributor to the continuing “releases” to the environment. However, the fact that elevated count rates are consistently recorded suggests that radioactivity is really present too as random fluctuations would be expected to occur in both directions (more and less counts).

f. The following table illustrates that the corporate software generally agrees with the Radcalc software regarding the LLD, and clearly shows that most recent samples showing releases of I-131 are, in fact, near or below the LLD levels. This suggests that these “releases” may not, in fact, be “real” and that radionuclide emissions based on these measurements may not exist.
<table>
<thead>
<tr>
<th>LLD</th>
<th>MDA</th>
<th>Sample CR</th>
<th>Radcalc</th>
</tr>
</thead>
<tbody>
<tr>
<td>(cpm)</td>
<td>(uCi)</td>
<td>(net cpm)</td>
<td>1 min LLD</td>
</tr>
<tr>
<td>446</td>
<td>99</td>
<td>0.00124</td>
<td>96</td>
</tr>
<tr>
<td>489</td>
<td>103</td>
<td>0.00138</td>
<td>107</td>
</tr>
<tr>
<td>433</td>
<td>97</td>
<td>0.00125</td>
<td>97</td>
</tr>
<tr>
<td>476</td>
<td>102</td>
<td>0.00127</td>
<td>99</td>
</tr>
<tr>
<td>444</td>
<td>98</td>
<td>0.00129</td>
<td>100</td>
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<tr>
<td>475</td>
<td>102</td>
<td>0.00127</td>
<td>99</td>
</tr>
<tr>
<td>583</td>
<td>113</td>
<td>0.00143</td>
<td>111</td>
</tr>
<tr>
<td>578</td>
<td>112</td>
<td>0.00139</td>
<td>108</td>
</tr>
</tbody>
</table>

Given the apparently systematic tendency for counts to be higher than background, however, it is possible that sample filters are contaminated with long-lived isotopes or that radon decay progeny are present in the sample filter and are being counted as I-131. The most likely radon progeny nuclide would be Pb-214, which has emits a 352 keV photon with 37% emission probability. This would clearly appear in the I-131 window (300-430 keV). Pb-214 has a half-life of 26.8 minutes, so re-counting any high-activity filters after 1-2 hours should show a marked drop in count rate that would, in turn, help to identify the presence of this isotope on the sample filter.

During air sampling, radon progeny (in this case, Pb-214) will accumulate on the filter paper, and the progeny present will simultaneously decay. With time, activity on the filter paper will reach equilibrium (saturation), and the equilibrium activity will depend on the sample flow rate, the half-life of the isotope in question, and the activity concentration in air. With a sample flow rate of 10 liters per minute, 1 pCi/l of Pb-214 in air will produce a saturation disintegration rate of 858 dpm on the filter. With a counting efficiency of 3.5%, the resulting count rate on the filter from Pb-214 is about 30 cpm for each pCi/l of radon present in air. The relevant equation is:

$$cpm_{sat} = \frac{\varepsilon \times A_{air} \times F}{\lambda} = 0.035 \times 2.22 \frac{dpm}{l} \times 10 \frac{l}{min} \times \frac{26.8 \text{min}}{\ln(2)} = 30 \text{cpm}$$

where e is the counting efficiency for the nuclide in question, A_{air} is the activity concentration in air, F is the sampler flow rate, and \( \lambda \) is the decay constant (\ln(2)/t_{1/2}) of the isotope of concern.

The above calculations show that the presence of radon progeny (specifically Pb-214) can lead to appreciable counts on the filter paper that might be misconstrued as I-131 emissions.
h. Based on the above, I recommend the following:
   i. Increase background and sample filter counting times to 10 minutes to achieve better counting statistics.
   ii. Any filters that give a count rate above the detection limit should be recounted after no less than one hour and the second count rate recorded to check for the presence of Pb-214.
   iii. When the sample filter count rate is less than the calculated MDA, it may be in appropriate to claim I-131 emissions. Accordingly, it may be advisable to change the corporate policy to recognize this, and to no longer include such “emissions” for affected facilities.

i. The above arguments apply only to radionuclide emissions in which the sample filter count rate is close to the MDA and/or LLD. It is obvious that neither counting statistics nor possible radon progeny can account for the dramatic rise in emissions earlier this year. Those increases are clearly real, and probably due to other factors mentioned above.

j. In addition to the use of different syringes and more-volatile iodine formulations, it is possible that the elevated levels of measured radionuclides are due to poor filter design. The existing filters seem to have some design weaknesses that would permit air to bypass the filters (e.g. loose-fitting covers, small gaps between filter elements, settling in the carbon filler, lack of HEPA pre-filters allowing clogging of carbon pores, short residence time for filtered air). It is likely that an improved filter design that addresses these weaknesses will also result in improved performance and reduced emissions.

After reviewing data from the past several months and after much discussion on this matter with the facility manager, the following findings seem appropriate:

1. The sample system is not designed in accordance with the recommendations of the American National Standards Institute (ANSI) in that the air flow rate is not isokinetic and the tubing is not heated. However, these deficiencies are unlikely to cause elevated readings for I-131 emissions.
2. Changes in sample system configuration and the possibility of non-iodine isotopes contaminating the sample (and elevating count rate) are also unlikely to be causing these elevated readings.
Why perform air sampling?

- Measure environmental releases
- Measure breathing zone airborne nuclide concentrations
- Measure results of accidental release
- Routine environmental monitoring (inside and outside facility)
Typical setup

- Sample point
- Sample lines
- Filter
- Pump
Sample point

- Should be towards the center of the airflow, in the air to be sampled
  - i.e. downstream of exhaust filter for environmental sampling
- Should be in a straight section of duct
Sample lines

- Should be as straight as possible and bends should be large radius
- Should be as short as possible
- Should slope downhill from sample point to filter if possible
- Should be material that will not react chemically with isotopes
- Should be smooth and warm enough to keep volatile nuclides from condensing
Filter

- Should be suitable to capture isotopes of interest
- Must be able to collect for entire sampling period (e.g. one week) without saturating or releasing materials
- Should be able to be removed and counted easily and efficiently
Sample pump

- Must be reliable – sample times may be as much as several months
- Must draw enough air to maintain isokinetic sampling conditions
Isokinetic sampling

- Ideally, the flow velocity in the sample tube should be equal to the flow velocity in the exhaust stream.
- Different flow rates can lead to over- or under-representing various particle sizes.
  - Ex: faster flow rate in sample tube can skew results towards larger particles.
Isokinetic sampling equations

\[ Velocity = \frac{Flowrate}{\pi r^2} \]

\[ Flowrate_{iso} = \frac{FR_{stack} \times r_{stack}^2}{r_{sample}^2} \]
Common tasks: Some sample procedures
SEALED SOURCE SURVEYS AND LEAK TESTS

I. Scope

This procedure covers performance of required surveys for sealed sources located on campus. These include leak tests and measurements of ambient radiation levels where applicable.

II. Purpose

It is necessary to leak test sealed sources that are in use to ensure that personnel are not exposed to radioactive contamination and to ensure that any measurements or calibrations made with these sources are accurate and correct. Federal regulations (10 CFR 35) and NRC Materials License No. 34-000293-02 require periodic leak testing.

III. References

10 CFR 20 (Standards for Protection Against Radiation)
10 CFR 35 (Medical Use of Byproduct Material)
Regulatory Guide 10.8 (Guide for the Preparation of Applications for Medical Use Programs)

IV. Equipment

- smear wipes
- cotton swabs
- protective gloves
- specimen tongs
- 20-ml liquid scintillation vials
- plastic sample vials
- portable radiation detection meter
- NRC 3 forms

V. Precautions

Follow approved procedures when handling any source. Always wear proper dosimetry and protective gloves. Be conscious of time, distance, and shielding. Sources may have high radiation levels on contact with the source. The following precautions shall be taken when surveying or leak testing high dose rate sources:

- Tongs and cotton swabs should be used for handling and smear wiping the sources whenever possible.
- Extremity and personal dosimetry shall be worn.
- Minimize the amount of time that the source is unshielded.
VI. Procedures

1. Contact RSO to arrange for testing and access to the source(s).

2. Ensure a current NRC Form 3 is posted in the source storage room - replace if missing or obsolete.

3. Verify all information listed on sealed source records is complete and accurate; correct or enter any incorrect, obsolete, or missing information.
   - If it is not be possible to obtain the model or serial number of the source itself. In this case, the model and serial numbers of the device may be used.
   - Records should also include the name, office, and telephone number of a person to contact with any questions which may arise regarding day-to-day use of the source.

4. Extend the source from the bottom of the nuclear gauge or open the gauge to expose the source or source holder.

5. Wipe outside of source or source capsule with dry cotton swab or smear wipe. Pay special attention to any seams or openings.

6. Survey the swab or smear wipe with a portable radiation detection instrument. If the count rate noted is in excess of 100 CPM above background, notify the RSO that the source may be leaking and is not to be used until further notice.

7. Place smear wipe or swab into LSV and break off tip (if swab used), then replace the lid on the vial. A gamma counter is also acceptable for counting smear wipes or cotton swabs if one is available and acceptable for the nuclide(s) in question. Cesium-137, for example, could be counted in this manner.

8. If the source is thought to be leaking, obtain smear wipes of the source storage container if possible and notify the RSO immediately.

9. Retract source into the gauge.

10. Count wipes on a liquid scintillation counter (or in gamma counter, if available and acceptable).

11. Record results on the appropriate record form. If the source is discovered to be leaking (or if leakage is confirmed) notify the RSO immediately. Notify the NRC as required by 10 CFR 35.59(e)(2).

12. Completed records shall be given to the RSO for review.
1.0 **Scope**

This procedure sets forth the specific requirements to be used for the operation and calibration of the Ludlum Model 12 Survey Meter for use at the SRS.

2.0 **Purpose**

The purpose of this procedure is to provide instructions for the operation and calibration of the Ludlum Model 12 Survey Meter in conjunction with Model 44-9 GM Pancake Probes, Model 43-5 Alpha Scintillation Probes, and Model 44-10 NaI Probes.

3.0 **References, Definitions and Developmental Resources**

3.1 **References**

3.1.1 Regulatory Guide 10.8, Rev. 2-1987, Guide for the Preparation of Applications for Medical Use Programs

3.1.2 ANSI N3.1-1987, Selection, Qualification and Training of Personnel For Nuclear Power Plants

3.2 **Definitions**

3.2.1 ACTIVITY - The rate of disintegration (transformation) or decay of radioactive material. The units of activity for the purposes of this procedure are disintegration per minute (dpm) or micro-Curies (FCi).

3.2.2 CALIBRATION CERTIFICATE - Document certifying calibration. It indicates the procedure used to calibrate the instrument and the record of data obtained prior to and during calibration. These documents are referred to as Instrument Service records.

3.2.3 CALIBRATION STICKER - Sticker attached directly to instrument which indicates calibration status of instrument.

3.2.4 CHECK SOURCE - A sample of radioactive material in which the exact quantity of radioactive material is not known but the type and energy of the emission is known. These sources are used for field response checks of radiation detection instrumentation.

3.2.5 PERFORMANCE CHECK - A check of a radiation detection instrument in which the performance of the instrument is checked.
against a reference source with an acceptance value of ±10% of the reference value.

3.2.6 REFERENCE STANDARD - A sample of radioactive material, usually with a long half-life, in which the number of radioactive atoms and the type of emission is known and is NIST traceable. These standards are used for calibration and performance checks of radiation detection instrumentation.

3.2.7 QUALIFIED USER - An individual that has demonstrated to management the skills and abilities to use instrumentation and is trained to perform specific program operations without supervision.

3.3 Developmental Resources

3.3.1 Instruction manual for the Ludlum Model 12 Survey Meter

3.3.2 ANSI N323-1978, Instrumentation Test and Calibration

4.0 Precautions, Limitations

4.1 Precautions

4.1.1 Take care not to puncture the thin mica window of the "pancake" G-M detector.

4.1.2 To prevent contamination of probes, avoid contact with the person(s) or object(s) being surveyed.

4.1.3 Prior to returning an instrument for calibration, the instrument shall be surveyed for radioactive contamination if it was used in an area where the potential for contamination existed.

4.2 Limitations

4.2.1 The operation of the Model 12 depends on the condition of the battery. Therefore, the battery check should be performed periodically to insure proper operation.

4.2.2 Calibration shall be performed annually, after maintenance is performed, if instrument fails the performance test or if its proper operation is in question.

4.2.3 A daily performance test is required when the instrument is in use.
4.2.4 "Pancake" GM Detectors shall be considered 10% efficient unless otherwise noted.

5.0 **Responsibilities and Qualifications**

5.1 **Responsibilities**

5.1.1 **Health Physics Supervisor**

5.1.1.1 Implementation of this procedure.

5.1.1.2 Periodic review of the adherence of personnel to the requirements of this procedure.

5.1.1.3 Performs periodic surveillance of the use and maintenance of the instrument.

5.1.2 **Health Physics Technician**

5.1.2.1 Ensures that the instrument is calibrated at specified intervals.

5.1.2.2 Documentation of all records in this procedure.

5.1.2.3 Notification to Health Physics Supervision of any unsafe or unusual conditions observed during operation of the instrument.

5.2 **Qualifications**

5.2.1 Health Physics Technicians shall be qualified in accordance with the requirements of ANSI 3.1 - 1987 to operate this instrument for any of the following surveys: job coverage and unconditional releases.

5.2.2 Jr. Health Physics Technicians may operate this instrument under supervision of a Health Physics Technician meeting the requirements of Section 5.2.1

6.0 **Procedure**

6.1 **Operation**
6.1.1 Verify that the instrument has a valid Calibration Sticker, and the performance test has been performed and initialed on the Performance Test Signoff Sticker.

6.1.2 Examine the instrument for any obvious physical damage which could interfere with its proper operation.

6.1.3 Perform a battery check on the instrument.

6.1.4 Set the audio, response (fast or slow), and range selector to the appropriate settings.

6.1.5 Proceed with operation in accordance with the desired use.

6.2 Calibration

6.2.1 Instrument Calibration shall be performed by an approved instrument Vendor Company.

6.2.2 The Calibration Certificate shall include as a minimum the following:

   6.2.2.1 The procedure used to calibrate the instrument.
   6.2.2.2 The technician who performed the calibration.
   6.2.2.3 Date calibrated and due date.
   6.2.2.4 The instrument "As Found" and "As Left" data.
   6.2.2.5 The instrument model and serial number.

6.3 Performance Test

6.3.1 Perform a performance test on the instrument and record all data on the Performance Test Log Sheet (HPF-009) for that instrument.

   **Note:** A performance test must be performed on each probe for that instrument. (i.e. GM Pancake and Alpha Scintillation Probe.)

6.3.2 Obtain the Performance Test source designated by the HPF-009 for the instrument and probe.

6.3.3 Record the information for each section of HPF-009.
6.3.4 Examine the instrument for any obvious physical damage which could interfere with its proper operation.

6.3.5 Verify that the instrument has a current Calibration Data Sticker, and Performance Test Signoff Sticker attached.

6.3.6 Perform a Battery Check to check that the battery is within the Batt OK range on the meter.

6.3.7 Expose the detector to the performance test source. If the response is within the designated range for the source, proceed to step 6.3.9. If the instrument fails, record "F" for fail on HPF-009 and remove the instrument from service for repair or calibration.

6.3.8 If the instrument fails any portion of the performance test, log the instrument as failing on the Performance Test Log Sheet, remove from service, and notify the Health Physics Supervisor or designee. Tag the instrument out of service.

6.3.9 If the instrument passes the performance test, record "P" for pass on HPF-009, then initial the Performance Test Signoff Sticker on the instrument and initial the Performance Test Log Sheet.

6.4 Maintenance

6.4.1 No special storage requirements.

6.4.2 Electronic maintenance (except probe and cable replacements) shall be performed by a vendor company in accordance with references.

7.0 Records

The following records will be generated as a result of using this procedure. Calibration records shall be kept on file until project completion, and then forwarded to the Branch Office.

7.1 Performance Test Log Sheet, HPF-009

8.0 Exhibits (see attachments)

8.1 Exhibit 1, Performance Test Log Sheet, HPF-009
OPERATION AND CALIBRATION OF THE LUDLUM MODELS 12S and 19 MICRO-R METERS

1.0 **Scope**
This procedure sets forth the specific requirements to be used for the operation and calibration of the Ludlum Models 12S and 19 micro-R meters. This procedure applies to R & R International, Inc. personnel who may use this instrument at the SRS.

2.0 **Purpose**
The purpose of this procedure is to provide instructions for the operation and calibration of the Ludlum Models 12S and 19 micro-R meters in accordance with the requirements specified in Reference 3.1.1.

3.0 **References, Definitions and Developmental Resources**

3.1 **References**

3.1.1 Regulatory Guide 10.8, Rev. 2-1987, Guide for the Preparation of Application for Medical Programs

3.1.2 ANSI N3.1-1987, Selection, Qualification, and Training of Personnel for Nuclear Power Plants

3.2 **Definitions**

3.2.1 ACTIVITY - The rate of disintegration (transformation) or decay of radioactive material. The units of activity for the purposes of this procedure are disintegration per minute (dpm) or micro-Curies (µCi).

3.2.2 CALIBRATION CERTIFICATE - Document certifying calibration. It indicates the procedure used to calibrate the instrument and the record of data obtained prior to and during calibration. These documents are referred to as Instrument Service records.

3.2.3 CALIBRATION STICKER - Sticker attached directly to instrument which indicates calibration status of instrument.

3.2.4 CHECK SOURCE - A sample of radioactive material in which the exact quantity of radioactive material is not known but the type and energy of the emission is known. These sources are used for field response checks of radiation detection instrumentation.
3.2.5 PERFORMANCE CHECK - A check of a radiation detection instrument in which the performance of the instrument is checked against a reference source with an acceptance value of ±10% of the reference value.

3.2.6 REFERENCE STANDARD - A sample of radioactive material, usually with a long half-life, in which the number of radioactive atoms and the type of emission is known and is NIST traceable. These standards are used for calibration and performance checks of radiation detection instrumentation.

3.2.7 QUALIFIED USER - An individual that has demonstrated to management the skills and abilities to use instrumentation and is trained to perform specific program operations without supervision.

3.3 Developmental Resources

3.3.1 LUDLUM Model 12S Micro-R Meter Instruction Manual

3.3.2 LUDLUM Model 19 Micro-R Meter Instruction Manual

3.3.3 ANSI-N323-1978, Radiation Protection Instrumentation Test and Calibration

4.0 Precautions and Limitations

4.1 Precautions

4.1.1 Due to the very low ranges only the 5,000 µR scale (Model 19) or 3,000 µR scale (Model 12S) can be calibrated to an actual source reading. All other scales will be calibrated to a pulse generator.

4.1.2 These detectors are not guaranteed light tight when outside of their instrument cases.

4.1.3 Prior to returning an instrument for calibration, the instrument shall be surveyed for radioactive contamination if the instrument was used in an area where the potential for contamination existed.
4.2 Limitations

4.2.1 Calibration shall be performed annually, after maintenance is performed, if the instrument fails the performance test or if its proper operation is in question.

4.2.2 This instrument shall be performance tested daily when in use in accordance with Section 6.3.

5.0 Responsibilities and Qualifications

5.1 Responsibilities

5.1.1 Health Physics Supervisor

5.1.1.1 Implementation of this procedure.

5.1.1.2 Periodic review of the adherence of personnel to the requirements of this procedure.

5.1.1.3 Performs periodic surveillance of the use and maintenance of the instrument.

5.1.2 Health Physics Technician

5.1.2.1 Ensures that the instrument is calibrated at specified intervals.

5.1.2.2 Documentation of all records in this procedure.

5.1.2.3 Notification to Health Physics Supervision of any unsafe or unusual conditions observed during operation of the instrument.

5.2 Qualifications

5.2.1 Health Physics Technicians shall be qualified in accordance with the requirements of ANSI 3.1 - 1987 to operate this instrument for any of the following surveys: job coverage, air sampling analysis and unconditional releases.

5.2.2 Jr. Health Physics Technicians may operate this instrument under supervision of a Health Physics Technician meeting the requirements of Section 5.2.1
6.0 Procedure

6.1 Operation

6.1.1 Verify that the instrument has a valid Calibration Sticker and the daily performance test has been done and initialed on the Performance Test Signoff sticker. If the performance test has not been performed, see Section 6.3.

6.1.2 Examine the instrument for any obvious physical damage which could interfere with its proper operation.

6.1.3 Perform a battery check by pressing the "BAT" button on the Model 19 or by switching to the "BAT" position on the Model 12S.

6.1.4 If the instrument fails any of the above checks, remove it from service and notify the Health Physics Supervisor.

6.1.5 Set the range multiplier to an appropriate range for the activity being investigated.

6.1.6 Read the meter after sufficient response time (i.e., the meter needle is relatively stable) changing ranges as necessary for the activity encountered. If the meter is used for an extended period of time, check the battery condition periodically to ensure proper operation.

6.1.7 Document all survey results in accordance with HP-OP-20.

6.2 Calibration

6.2.1 Instrument Calibration shall be performed by an approved instrument Vendor Company.

6.2.2 The Calibration Certificate shall include as a minimum the following items:

   6.2.2.1 The procedure used to calibrate the instrument.
   6.2.2.2 The technician who performed the calibration.
   6.2.2.3 Date calibrated and due date.
   6.2.2.4 The instrument "As Found" and "As Left" data.
   6.2.2.5 The instrument model and serial number.
6.3 Performance Test

6.3.1 Perform a performance test on the instrument and record all data on HPF-009, Performance Test Log Sheet.

6.3.2 Obtain the performance test source designated on HPF-009 for the instrument. Record the information for each Section of HPF-009.

6.3.3 Examine the instrument for any obvious physical damage which could interfere with its proper operation.

6.3.4 Verify that the instrument has a current Calibration Data Sticker and Performance Test Signoff Sticker.

6.3.5 Perform a battery check by turning the selector switch to BAT (Model 12S) or by turning the unit to 5000 µR/hr scale and depressing "BAT" button (Model 19). If the unit does not read in BATTERY area, replace the batteries.

6.3.6 Expose the center of the detector to the designated source. If the reading is within the range on HPF-009, record "P" for "PASS" on HPF-009. If the reading is outside the range, record "F" for "FAIL" on HPF-009 and remove the instrument from service.

6.3.7 If the instrument passes all sections of the performance test, initial the Performance Test Signoff Sticker and complete HPF-009.

Note: Due to the extremely low ranges incorporated in these instruments, only the high scales may be performance tested with an actual source reading.

6.4 Maintenance

6.4.1 No special storage requirements.

6.4.2 Electronic maintenance shall be performed by a Vendor company in accordance with references.

6.4.3 Records of Maintenance shall be maintained with the calibration records.

6.4.4 All maintenance shall be performed in accordance with the manufacturer’s specifications.
6.4.5 When the instrument is repaired, the HP Supervisor or designee will review the nature of the repair and determine if a calibration is required.

6.4.6 If re-calibration is not required, performance test the instrument (as per Step 6.3) prior to returning the instrument to service.

7.0 **Records**
The following records will be generated as a result of using this procedure.

7.1 Performance Test Log Sheet, HPF-009

8.0 **Forms**

8.1 HPF-009, Performance Test Log Sheet - See attachments

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**DECONTAMINATION AND RELEASE OF MATERIAL**

1.0 **Scope**

This procedure sets forth specific requirements, methods and techniques used for the removal of contamination from equipment and materials.

2.0 **Purpose**

This procedure provides guidance for equipment and material decontamination and to minimize the potential for unintentionally releasing contaminated items from Restricted Areas.

3.0 **References and Definitions**

3.1 **References**

3.1.1 10 CFR 20 (1-1-92), Standard for Protection Against Radiation.


3.1.3 HP-OP-20 - Performing Radiation and Contamination Surveys.

3.2 **Definitions**
Activity. The rate of disintegration or decay of radioactive material. The units of activity for the purposes of this procedure are disintegrations per minute in micro-Curies for loose contamination, and disintegrations per minute, milliroentgen, or millirad for fixed contamination. These terms are defined in 10 CFR 20.

Contamination. Deposition of radioactive material in any place it is not desired, particularly where its presence may be harmful. The harm may be actual exposure to individuals or release of the material to the environment or general public. Contamination may be a result of the presence of radionuclides emitting alpha, beta, or gamma radiation.

Fixed Contamination. Radioactive contamination that is not readily removed from a surface by applying light to moderate pressure and wiping with a paper or cloth disc smear.

Loose Contamination. Radioactive contamination that is readily removed from a surface by applying light to moderate pressure and wiping with a paper or cloth disc smear.

Minimum Detectable Activity (MDA). For purposes of this procedure, MDA for removable radioactive contamination is defined as the smallest amount of activity that will yield a net count with a 95% confidence level, based upon the background count rate of the counting system used.

Release for Unconditional Use. A level of radioactive material that is acceptable for use on property without license conditions or controls. Under normal circumstances, authorized limits for residual radioactive material are set to, or below, the values specified in USNRC Regulatory Guide 1.86.

Restricted Area - An area, access to which is limited by the licensee for the purposes of protecting individuals against undue risks from exposure to radiation and radioactive materials. Restricted Area does not include areas used as residential quarters, but separate rooms in a residential building may be set apart as a Restricted Area.

4.0 Precautions and Limitations

4.1 Precautions
4.1.1 Vacuums used for decontamination purposes shall have a HEPA filtration system, as necessary.

4.1.2 When using water to decontaminate nonporous surfaces, waste water must be contained for sampling before being disposed of.

4.1.3 Care should be taken when choosing types of detergents, agents, solvents and/or acids to prevent generating mixed waste.

4.1.4 When using a sandblasting method of decontamination, local containment should be used to prevent the spread of contamination.

4.1.5 Surveys shall be performed in accordance with HP-OP-20.

4.1.6 Audible response shall be used on direct frisk surveys using portable instrumentation.
4.2 Limitations

4.2.1 When using vacuums, the machine may become contaminated.

4.2.2 The maximum probe speed of instruments used during direct frisk survey shall be 5 cm/sec.

5.0 Responsibilities and Qualifications

5.1 Responsibilities

5.1.1 Health Physics Supervisor

5.1.1.1 Implementation of this procedure.

5.1.1.2 Initial qualification of technicians and periodic review of the adherence of personnel to the requirements of this procedure.

5.1.1.3 Signature approval to release material or equipment, or to permit use of material or equipment with fixed activity above the limits specified in Section 6.1 of this procedure, but not above the values specified in Regulatory Guide 1.86.

5.1.2 Health Physics Technicians

5.1.2.1 Performing the requirements of this procedure.

5.1.2.2 Adhere to other procedures referred to in this procedure.

5.1.3 Authorization to release materials and equipment up to the ALARA limits specified in 6.1 of this procedure.

5.2 Qualifications

5.2.1 All personnel performing equipment and material decontamination shall be qualified on this procedure prior to performing the task.
6.0 Procedure

6.1 ALARA Goals for Unconditional Release of Equipment and Materials:

<table>
<thead>
<tr>
<th>EMISSION</th>
<th>TOTAL ACTIVITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha</td>
<td>&lt; 20 dpm/100 cm²</td>
</tr>
<tr>
<td>Beta</td>
<td>&lt; 100 dpm/100 cm²</td>
</tr>
</tbody>
</table>

6.2 Material and Equipment Release Limits (all limits in dpm/100 cm²)

<table>
<thead>
<tr>
<th>NUCLIDE</th>
<th>AVERAGE</th>
<th>MAXIMUM</th>
<th>REMOVABLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unat, U-235, U-238 (alpha)</td>
<td>5.000</td>
<td>15,000</td>
<td>1,000</td>
</tr>
<tr>
<td>Transuranics, Ra-226, Ra-228, Th-230, Th-228, Pa-231, Ac-227, I-125, I-129</td>
<td>100</td>
<td>300</td>
<td>20</td>
</tr>
<tr>
<td>Th-Nat, Th-232, Sr-90, Ra-223, Ra-224, U-232, I-126, I-131, I-133</td>
<td>1,000</td>
<td>3,000</td>
<td>200</td>
</tr>
<tr>
<td>Beta-gamma emitters</td>
<td>5,000</td>
<td>15,000</td>
<td>1,000</td>
</tr>
</tbody>
</table>

6.3 Decontamination Procedure

6.3.1 Make a reasonable effort to remove all physical signs of contamination (e.g., visible dust, dirt, mud, or rocks).

6.3.2 Select an effective technique, such as vacuuming or using shovels, trowels, brushes, or brooms.

6.3.3 Use vacuum as the preferred method for porous surfaces.

6.3.4 Dispose of all material removed during decontamination attempts as radiologically contaminated waste.
6.3.5 After each decontamination evolution, dry and re-survey the equipment or material.

6.4 Survey Procedure

6.4.1 Perform a direct frisk of 100% of all accessible areas of the equipment or material, in accordance with the instrument's operation procedure.

6.4.1.1 If the frisk indicates radioactive material on the surface of the equipment or material at a level lower than the ALARA goals, then the equipment or material may be released.

6.4.1.2 If the frisk indicates radioactive material on the surface of the equipment or material at a level greater than the ALARA goals, but below Regulatory limits, the material or equipment can be released with supervisory permission. If the frisk indicates a level greater than regulatory limits, the material may not be released.

6.4.2 If the equipment or material's surface area is greater than 100 cm$^2$ then perform a large area smear.

6.4.2.1 If the presence of radioactive material is found above background, the equipment shall be treated as contaminated until a detailed disc smear survey is performed.

6.4.3 Perform Disc smear of the effective accessible surface area.

6.4.4 Count and document the smears in accordance with procedure HP-OP-20, Performing Radiation and Contamination Surveys.

6.4.4.1 Record smear data

6.4.4.2 If the smear results indicate transferable activity above the ALARA goals, but below the values listed in Section 6.2 of this procedures, the material or equipment may be released with supervisory permission. However, if
NOTE: Every effort shall be made to decontaminate the material and/or equipment to a level below the limits set forth in USNRC Reg. Guide 1.86, and preferably below the ALARA limits in this procedure.

Material or equipment released unconditionally shall be documented on HPF-002, Health Physics Survey Report, together with an associated survey log number.

7.0 Records/Forms

The following records are created by the use of this procedures. These records shall be maintained for one year in an active file and archived thereafter.

7.1 Health Physics Survey Report (HPF-002), found in HP-OP-20.

7.2 Counting Room Analysis Report (HPF-004), found in HP-OP-20.

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SURVEY OF RADIOACTIVE MATERIAL SHIPMENTS

1.0 Scope

This procedure applies to the shipment of radioactive material and waste at the SRS.

2.0 Purpose

This procedure describes the radiological survey requirements for outgoing shipments of radioactive materials and waste.

3.0 References and Definitions

3.1 References

3.1.1 10 CFR 20, Standards for Protection Against Radiation

3.1.2 10 CFR 71, Transportation of Radioactive Material
3.2 Definitions

3.2.1 Radioactive Material - For the purposes of this procedure, radioactive material includes any material, equipment, or system component determined to be contaminated or suspected of being contaminated. Items located in known or suspected Contamination or Airborne Radioactivity Areas are considered radioactive material. Radioactive material also includes activated material, sealed and unsealed sources, and materials that emit radiation.

3.2.2 Transport Index - The Transport Index (TI) is the maximum measured dose rate at one (1) meter from the surface of the package, rounded to the nearest 0.1 mrem/hr. The TI is required to be listed on the shipping label per U.S. Department of Transportation (DOT) regulations.

4.0 Precautions and Limitations

4.1 The instruments selected to conduct the radiological surveys should be appropriate for the type of radiation to be detected (i.e., alpha frisker for alpha contamination, etc).

4.2 All materials that are transferred out of radiological areas are subject to the release survey requirements that are detailed in HP-OP-21.

4.3 All waste generated in Contamination and Airborne Radioactivity areas shall be considered radioactive waste.

4.4 All radioactive waste containers shall be properly packaged and labeled according to the requirements of Reference 3.1.2.

4.5 The instrument Minimum Detectable Activities (MDAs) should be equal to or less than the removable contamination limits shown in Attachment 1.

4.6 Intake air filters shall be treated as non-radioactive waste if the direct survey of the surfaces with portable instrumentation, after 1 week of decay time, is less than the instrument MDA.

4.7 Smear wipes shall be treated as non-radioactive waste if the direct survey of the surfaces with portable instrumentation is less than the instrument MDA.

4.8 The transport vehicle shall be surveyed prior to loading to verify that it complies with the established contamination limits.
5.0 **Responsibilities**

5.1 The Health Physics Supervisor shall be responsible for:

5.1.1 The implementation and administration of this procedure.

5.1.2 Designation of personnel necessary to carry out the requirement of the procedure.

5.1.3 Review of documents generated during the performance of this procedure.

5.2 Health Physics Technicians shall be responsible for the performance of the requirements set forth in this procedure.

6.0 **Procedure**

6.1 **External Radiological Surveys of Outgoing Shipments**

6.1.1 Visually inspect the shipping container and note any damage on the radiological survey record.

6.1.2 Perform an external radiation survey to determine the maximum dose rate at 1 meter from the shipping container. Survey at 1 meter from all sides, including the top and bottom of the container, as appropriate.

6.1.3 Perform a removable contamination survey of the exterior surfaces of the container to be shipped.

6.1.3.1 Wipe the surface of the container with a masslin cloth or other absorbent material.

6.1.3.2 Survey the swipe with the appropriate survey instrument(s).

6.1.4 If any removable contamination is detected, the container should be decontaminated and step 6.1.3 repeated.

6.1.5 If further decontamination of the container is impractical, a quantitative removable contamination survey must be performed. Smears shall be taken over 100 cm$^2$ areas. Determine the maximum contamination level in dpm/cm$^2$ (see note 2 to Attachment 1).
6.1.6 Record the results of the radiation and contamination surveys on the radiological Survey Form

6.2 Transport Vehicle Surveys for Shipment of Radioactive Materials

6.2.1 For non-exclusive use vehicles transporting single packages with low dose rates, this survey is not necessary.

6.2.2 Perform an external radiation survey to determine the maximum dose rate at any occupied location in the vehicle cab.

6.2.3 Survey the surfaces of the transport vehicle to determine the maximum dose rate present.

6.2.4 Perform an external radiation survey to determine the maximum dose rate at two (2) meters from the surface of the transport vehicle (or if a flatbed trailer, at a point two meters from the vertical planes at the edges of the trailer).

6.2.5 Record the results of the survey on a Health Physics Survey Report (HPF-002).

7.0 Records

7.1 Health Physics Survey Report, HPF-002

7.2 Radioactive Shipment Records (Copy to be kept with Survey Report)

8.0 Exhibits

8.1 Exhibit 1, Contamination Limits for Shipments of Radioactive Material

8.2 Exhibit 2, External Radiation Limits for Shipments of Radioactive Material
1 Purpose
1.1 The purpose of this procedure is to define how to conduct radioactive contamination surveys. The performance of periodic surveys and the way in which they are performed are required under sections of the New York Code of Rules and Regulations. This procedure is based on the model radiological survey procedure developed by the State of New York. In this procedure, steps which are mandated by New York law are italicized.

2 Scope
2.1 This procedure applies to all research laboratories at the University of Rochester and Strong Medical Center.

3 References
3.1 NYS DOH, Bureau of Environmental Protection Radiation Guide Series 10.1 rev. 2, Appendix G
3.2 NYS DOH, Bureau of Environmental Protection Radiation Guide Series 10.2 rev. 1, Appendix I
3.3 New York State Sanitary Code Chapter I, Part 16

4 Equipment
4.1 one inch (2.5 cm) diameter filter paper smear wipes (or equivalent)
4.2 impermeable gloves
4.3 radiation detection instrument (liquid scintillation counter or hand-held meter)

5 Precautions
5.1 Protective gloves should be worn when smear wiping potentially-contaminated surfaces
5.2 Wipes should be separated to avoid cross-contamination
5.3 Do not use a single smear wipe to survey multiple 100 cm² locations or to survey areas significantly larger than 100 cm² (for example, one smear
wipe may not be used to survey an entire laboratory bench top or to survey several 100 cm² locations on a work bench)

6 Procedure for conducting smear wipe surveys for radioactive contamination

6.1 Research laboratories where unsealed sources of radioactive material are used shall be surveyed monthly.

6.2 Pay special attention to posted work areas, hoods, waste disposal areas, storage areas, floor surfaces. Also check non-use areas in labs such as desks, trash containers, phones and areas where possible cross contamination might occur.

6.3 Conduct wipe tests to measure contamination levels from H-3, C-14, S-35, Ni-63 and/or other beta-emitting radionuclides with decay energies less than 300 KeV. Wipe tests may be used to detect other beta-emitting radionuclides (e.g. P-32) if desired. Wipe tests are performed by wiping a piece of dry filter paper or equivalent over an area of 100 square centimeters.

6.4 Count smear wipes for removable contamination in an appropriate counting device (i.e. liquid scintillation counter or beta counting system).

6.5 Record results as described below

7 Procedure for conducting a meter survey for radioactive contamination

7.1 Radiation meter surveys may only be performed for isotopes emitting gamma radiation or beta particles with an energy greater than 300 KeV.

7.2 Prior to conducting a radiation meter survey, the following checks shall be performed:

7.2.1 All radiation detection instruments must be calibrated annually. Verify the meter to be used is in calibration.

7.2.2 Verify proper battery operation by taking the main switch to the “Battery Test” position (or equivalent) and observing the needle deflection to the “Battery Test” (or equivalent) position.

7.2.3 Verify the physical condition of the instrument is satisfactory.

7.2.4 Verify the instrument cable is intact, in good physical condition, and does not have any cuts or tears in the insulation.

7.2.5 Set the audible response switch to the “On” position and set the response switch to the “F” (fast response) position.

7.2.6 Verify the meter has been checked for proper response against a source of known strength on the day of use.

7.3 Hold the radiation detector between 0.5 and 1 cm from the surface to be
surveyed and move at a rate of 3-5 cm per second. **NOTE:** holding the probe at an excessive distance or moving the probe too rapidly may result in not detecting radioactive contamination. Holding the probe too close to the surface surveyed may result in contamination of the probe.

7.4 Record the highest net count rate reading noted on the survey map as noted.

7.4.1 To determine the net count rate, subtract background count rate from the instrument reading. For example, if you have 50 cpm from background radiation (measured outside the laboratory) and the instrument reads 300 cpm, your net count rate is 250 cpm.

7.4.2 **Convert this count rate to a disintegration rate using the meter efficiency for the isotope in use.** For example, if a count rate of 250 counts per minute is noted for P-32 and the meter efficiency for P-32 is 50%, the disintegration rate is 500 disintegrations per minute (dpm).

8 **Recording survey results**

8.1 *Permanent records will be kept of all survey results, including negative results.* These records shall be maintained in the radiation safety record binder maintained by each radiation permit holder.

8.2 *The record will include location, date, serial numbers of instruments used, results of the daily instrument response check (see 7.2.6, above), and the name of the person conducting survey.* Record background count rate in units of counts per minute if a direct radiation meter survey was used instead of smear wipes.

8.3 The survey record will include drawings of areas surveyed, identifying relevant fixtures such as active storage areas, waste, and work areas.

8.4 *Results shall be noted in units of disintegrations per minute per 100 cm².* To convert instrument count rates to disintegration rates, divide the count rate by the instrument efficiency for the specific nuclide detected.

8.5 The RSO will be immediately notified if contamination levels exceed **500** dpm per 100 cm². Any areas containing removable contamination in excess of **200** dpm per 100 cm² shall be decontaminated to less than these levels.
Instrument use – performing common tasks

______________________________________________________________________
______________________________________________________________________
______________________________________________________________________
Surveys

• Periodic radiation and/or contamination surveys
  – Daily, weekly, or monthly, depending on operating circumstances
  – Frequency depends on level of use
• “Special” surveys
  – Post-work surveys if handling isotopes
  – Post-maintenance
  – After any significant change or work that could affect shielding or other characteristics
Pre-survey checks

- Confirm proper detector for survey
- Verify meter calibrated within last year
- Verify physical integrity of meter and cable
- Perform battery check
- Perform response check against source of known strength (+/-20% of ave. counts)
- Verify switch positions if appropriate (audible “on” and response “f” or “fast”)
Contamination surveys

- Perform pre-survey meter checks
- Hold detector no more than ½ inch from surface to be surveyed
- Move detector at no more than 2”/second
- Survey 100% of surface if possible
- Watch probe to ensure proper survey while listening to detector – if you hear an increase in count rate, see if area is contaminated
Contamination surveys (con’t)

- Record any area in which count rate increases appreciably (e.g. 50 cpm for a GM, 100 – 200 for thin-xtal NaI)
- Must record net cpm and dpm on survey record
  - $\text{Cpm} - \text{bkg} = \text{net cpm}$
  - $\text{Cpm/meter efficiency} = \text{dpm}$
Example

- Say background levels are 50 cpm with a GM probe
- At a certain location, you read 130 cpm
- 130-50 = 80 net cpm
- If meter efficiency is 40%:
  - dpm = 80 cpm/0.40 = 200 dpm
Smear wipe surveys

- May have to perform smear wipe survey for isotopes with low meter efficiency (such as H-3, C-14, S-35)
- Smear wipes are dry filter paper, wiped over 100 cm²
- Want to avoid cross-contamination of wipes
- Want to avoid cross-contaminating surfaces
- Usually counted in proportional counter, gamma counter, or scintillation counter
Sealed source checks

- Required to inventory sealed sources either quarterly or semi-annually
- Required to leak test sealed sources with same periodicity
  - Some sources do not require leak testing – check your license or regulations
- Performing a leak test does not necessarily count as an inventory check – must record both events separately
Importance of surveys

- If you do not have dosimetry records, your survey records are the only means you have to combat unjustified radiation injury claims
- For this reason, properly performing complete surveys and retaining survey records is crucial
- Equally important is ensuring your survey equipment is properly maintained and calibrated
Leak testing

- Must report significant source leakage (check your regulations for amount)
- Must be able to show that test methodology will detect at or below contamination limit
- Several acceptable methods of leak testing and inventory
Leak test methods

- Best to directly wipe 100% of source capsule
  - May wish to consider holding source and wipe with tongs to reduce finger dose
- Can also wipe area around source if source is not directly accessible
- Can also wipe outside of source holder
Inventory methods

- Best to visually sight the source
- Can also verify source in sealed container that has been sealed since last inventory
- Can also verify operability of device that relies on presence of source
- Other methods may be acceptable – check with the source/device manufacturer and regulators
Radiation surveys

- Use appropriate meter
  - Ion chamber, micro-R meter, etc.
- For general area surveys, hold meter at waist level (about 1 m above ground) and walk slowly through area being surveyed
- “General area” is 30 cm (1 foot) from any surface
- “On contact” used to measure hot spots – usually taken to be 1” from surface or point surveyed
- Record highest readings as well as area readings
Some trouble-shooting: common problems

• Elevated counts, no contamination
• Spurious high and/or low counts or erratic readings
• No readings (including background)
Elevated count rate – possible causes (checks)

- Light leak (scintillation probes only)
  - Cover probe, then uncover; compare counts
  - Light leak indicated if counts ↑ when probed exposed to light
- Contaminated probe
  - Move probe a meter or so from survey location
  - If high counts remain, probe may be contaminated
- High radiation levels
  - Hold probe near body
  - If readings drop, high counts may be due to high radiation levels
Erratic readings

- Most likely cause is a short or open circuit in the cable (very common)
- If high or low counts can be reproduced by jiggling cable or holding probe in a certain position relative to meter, you should suspect a cable problem
- Use another meter to survey location OR change cable on problematic meter
No readings

- Most likely cause is dead batteries
  - Perform battery check
  - Replace batteries
- Also possible that detector is broken or disconnected
  - If batteries are OK, use check source to test meter response
  - Examine detector and detector window for breakage, replace if necessary
If all else fails....

- Change cable and probe OR
- Send meter for re-calibration
- Send meter for repair
- Buy a new meter
Responding to radiological accidents and emergencies

Introduction
Accidents happen. Including accidents involving radiation or radioactivity. In the 20+ years I’ve been working with radiation and radioactivity, I’ve lost count of the number of spills, skin contamination, high radiation levels, and other accidents I’ve had to deal with in some capacity or other. And anyone working with radiation or radioactivity will, at some point, be in a position of having their own radiological incident to contend with. And, of course, we now also have to consider the possibility of deliberate mis-use of radioactive materials as a part of a terrorist attack. This is a good time to dust off the response plans to see if we are ready to properly address any untoward incidents that might occur.

In this article, we will address some general procedures that apply to many radiological incidents as well as some general steps to take in some specific cases. These are guidelines only – every incident is unique. But some general guidelines to generic situations can be applied to the specific situations with suitable modifications. So, in this article, I’ll discuss radioactive spills, skin contamination, traffic accidents, the loss of radioactive materials, and the use of radiological dispersal devices (RDDs, also called “dirty” bombs”).

General guidelines
In most cases, radiological incidents are not life-threatening and, in fact, pose little actual physical risk. The radioactivity is a nuisance, a regulatory problem, and a complicating factor, but it is rarely potentially harmful. So the first general rule should be “Don’t panic.” Take the opportunity to think through your actions before springing into action to try to save the day. By so doing, you are less likely to take rash actions that could well end up making things worse rather than better.

In general, radiological hazards will pose little risk to people involved in a radiological accident. This means that emergency responders and medical personnel are very unlikely to be at risk from victims or patients, no matter how heavily contaminated they are. This means that victims and patients should be cared for as rapidly as required by their injuries – the badly injured or critical should be cared for immediately, and lightly injured patients may be safely decontaminated or wrapped to contain the contamination so that they do not contaminate an ambulance or hospital emergency room.

Actions should be taken to try to minimize exposure to people near and responding to the incident. Unless actually involved in incident response, everyone should stay at the greatest distance possible, they should minimize the amount of time they’re in a controlled area, they should try to interpose shielding between themselves and the sources of radiation, and they should try to don appropriate PPE (such as shoe covers, gloves, and coveralls when involved in a spill) if possible.
Specific incidents
There are over 17,000 radioactive materials licensees in the United States and the vast majority of these licensees are relatively small industrial users who possess either radioactive gauges, small radioactive sources, or relatively minor amounts of unsealed radioactive materials. There are also a large number of small medical licensees, colleges, and radiopharmaceutical vendors. Large organizations, such as nuclear power plants, nuclear fuel cycle facilities, or major research universities constitute only a tiny fraction of all licensees and they are likely to have full-time health physics staff to handle radiological problems. It is the former group, the relatively small licensees, for whom this article is written and they are likely to experience only a relatively small variety of types of incidents – those noted below.

Spill of radioactive material
It’s easy to cause a spill – knocking over a small vial of radioactive materials can cause one, as can accidentally ejecting the contents of a pipettor or dropping a sample tube or even just having a drop fall from a beaker or bottle. Radioactive spills cause contamination in the area of the spill, they can lead to the contamination of personnel, and they can result in the spread of contamination to office areas or homes. Minor spills can often be cleaned up fairly easily; major spills can cause problems.

There are some actions that can be taken immediately in the event of a spill. The acronym we use at our facility (and what we were taught in the nuclear Navy) was SWIM – Stop the spill, Warn others of the spill, Isolate the area, and Minimize exposure to radiation. It is not necessary to follow these steps in this order, but completing these actions will help to reduce the impact of the event.

Stopping the spill is not the same as cleaning it up; it is taking actions to keep the spill from getting worse. If a container fell over, right it (wearing protective gloves, hopefully!) cap or cover it, and place it in a pail or deep tray. Next, try to place absorbent materials over the spilled liquid or, if it is a powder, cover it with dampened wipes or rags to keep it from blowing around. You are not trying to clean up the spill at this point, you are simply trying to limit the amount of spilled material and its extent.

Warning others may be the first thing that happens – most people make some comment when they cause a spill. You will want to warn others not to walk into the spill area, to ask for help with the cleanup, and anyone nearby who might have been contaminated by the spill should stand fast to keep them from spreading contamination. This should also include contacting the radiation safety officer and other radiation safety staff, plus anyone else on your incident call-up list. Workers should be able to contact the RSO or a competent alternative at any time in the event of a radiological incident, so the RSO’s pager and/or telephone number(s) should be made available to radiation workers or to Security officers as appropriate in the event of after-hours spills.

Isolate the area involved in the spill. There are several reasons to do this; you want to keep people out of the spill so they don’t get contaminated, you will need room to work on cleaning up the spill, and anyone within the spill boundaries should be considered
potentially contaminated. You should use rope or tape or some other physical barrier whenever possible, even if you are isolating an entire room. Simply posting a door sign may not work – many people just don’t read door signs – but they will stop before crossing a rope or tape boundary. At my facility, nobody is permitted to cross a spill boundary to enter an area unless they are wearing gloves, shoe covers, and a lab coat; and nobody is allowed to exit a spill area unless they are surveyed out of the area by Radiation Safety staff. We have had incidents in the past in which junior staff have let themselves be intimidated by senior staff, letting them enter or leave spill areas and spreading contamination. Setting this policy and supporting those who enforce it takes the junior staff off the hook and we have had no such problems since its implementation. Once spill boundaries are established, they should be verified by surveying on the “clean” side to confirm that all of the contamination is contained within the boundaries.

**Minimizing exposure** is as much a philosophical point as a procedure. As noted above, spills are not life-endangering. There is time to consider the best way to address the problem. Think about the situation you are faced with – do you have proper PPE, do you have the materials you need to survey and decontaminated efficiently, are you wearing respiratory protection (if the materials are volatile), do you have dosimetry, do you know where the highest radiation areas are (and how to work around them), and so forth. By taking a moment to consider your situation and planning on how to best address it, you will be helping to reduce your exposure and that of others in the area.

Once you have completed these immediate actions, the spill should not worsen, and it is possible to begin survey and clean-up. In general, it is better to work from the outer spill areas towards the center and, in the case of multi-level spills (say, a spill on a table that drips to the floor) to work from the top towards the bottom. In most cases, spills may be cleaned up with standard commercial cleaners, although spills involving radioactive metals (such as Cs-137 or Co-60) may benefit from the use of specialty products.

Contamination surveys should be performed with an appropriate detector for the type of radiation emitted by the isotope spilled. This information is summarized in the accompanying table. A direct frisk will reveal the total amount (fixed plus removable) of contamination present in an area while a smear wipe will only show how much removable contamination is there, so there is a value in performing both types of surveys. However, some isotopes (H-3, in particular) are very difficult to survey for by direct frisk and it’s possible that the only reliable information about contamination levels will be obtained via smear wipe surveys.

**Skin contamination**
As with radioactive spills, skin contamination is not life-endangering although, in rare cases, localized skin burns can result from “hot particles”. This means that workers shouldn’t panic over skin contamination, but also that they should work quickly to remove the contaminant. The immediate actions in case of skin contamination can be remembered as “CCC”:
• Contact the RSO to inform him/her about the skin contamination
• Count the amount of contamination on the skin with an appropriate detector and write this number down. This will later be used to help calculate skin dose and/or possible uptake from the contamination
• Clean the contaminated area by going to the nearest sink and washing with mild soap and cool to warm water. While cleaning, a general rule is to not take any actions that are painful or uncomfortable – in most cases, the skin acts as a barrier to keep contamination on the outside of the body, and it is important to not breach this barrier.

While decontaminating, the worker should survey periodically; if the count rate continues to decrease then the decontamination is having an effect and should continue. If, however, the count rate stabilizes or if the skin starts to redden or bleed, decontamination should stop until the RSO or another qualified person arrives to determine what should be done. In some cases, simply wrapping the contaminated area in plastic can help – the contamination is “sweated” out – but this is obviously not a good idea for facial contamination! More drastic decontamination measures should ONLY be taken if there is a need (because of very high contamination levels) AND if advised by a competent radiation safety professional.

Following decontamination it may be necessary to calculate radiation dose to the skin or to internal organs. These should be done by either a staff health physicist or by a consultant because these calculations can be complex and it is necessary to make sure they are done correctly. There are some software programs that will help with these calculations, but they give the best results in the hands of a radiation safety professional. In the event a person is contaminated by something that will be absorbed through the skin (e.g. tritiated water or many iodine compounds) it may also be necessary to take urine samples or to perform thyroid counts to check for uptake of isotope. This determination can also be made by a health physicist.

Traffic accidents involving radioactive materials
Every day, radioactive materials are transported in thousands of vehicles. These include soil density gauges, radiopharmaceuticals, small vials of research isotopes, radioactive waste, nuclear reactor fuel, and more. Although rare, these vehicles are sometimes involved in accidents that may or may not release radioactive materials. It is imperative that any vehicular accident involving radioactivity be reported immediately to the company (if appropriate) and to emergency response personnel so that injured people can be cared for and so that the radioactive materials can be recovered and contained.

The primary concern for any vehicular accident is the health of the people involved in the accident. Injured personnel must be cared for first, and stabilized if necessary. Contaminated (or potentially contaminated) people should be cared for without regard to their contamination if necessary. However, it may be prudent to inform emergency response and medical personnel of the contamination (and that it poses no risk to them).
so that the victim can be wrapped or decontaminated to minimize contamination spread to the ambulance or medical facility. Even this step is not a necessity, but it will help to reduce the chance that a vehicle or medical room will require decontamination prior to use for other patients.

After injured personnel are cared for, the radioactive materials must be accounted for, contained, and recovered as appropriate. The physical form of the radioactive materials (e.g. liquid, gas, solid), the manner in which they are contained, and the severity of the accident will determine the amount and spread of contamination. For example, a soil density gauge packed in its case will likely escape unscathed from all but the most severe accidents, while a jug of radioactive liquid may contaminate the inside of the vehicle and the ground it drips onto. This phase of the accident recovery should include donning appropriate protective equipment (say, gloves, protective coveralls, and shoe covers), opening the storage area, and assessing the physical condition of the radioactive materials storage container. If there is obvious leakage into the vehicle interior or onto the ground, or if contamination surveys show materials were released, they must be contained and cleaned up as necessary.

**Loss of radioactive materials**

Radioactive materials must be accounted for at all times, and the loss of radioactive materials must be taken seriously. At the least, the loss of radioactive materials raises the concern of accidental exposure of the public or release to the environment. At worst, we must also consider the possibility of deliberate misuse. In the past, such misuse included attempted poisoning and deliberate contamination. Today, to these concerns we must also consider that missing radioactive materials may also be used in a terrorist attack. In any event, all cases of missing radioactive materials must be investigated and explained, and every effort should be made to locate and recover the missing materials. And, if enough material is lost, it may need to be reported to regulatory authorities, depending on the amount of radioactivity lost and the potential radiation dose to the public.

According to 10 CFR Section 20.2201 (Reports of theft or loss of licensed material):

Each licensee shall report by telephone as follows:

(i) Immediately after its occurrence becomes known to the licensee, any lost, stolen, or missing licensed material in an aggregate quantity equal to or greater than 1,000 times the quantity specified in appendix C to part 20 under such circumstances that it appears to the licensee that an exposure could result to persons in unrestricted areas; or

(ii) Within 30 days after the occurrence of any lost, stolen, or missing licensed material becomes known to the licensee, all licensed material in a quantity greater than 10 times the quantity specified in appendix C to part 20 that is still missing at this time.
Written reports. (1) Each licensee required to make a report under paragraph (a) of this section shall, within 30 days after making the telephone report, make a written report setting forth the following information:

(i) A description of the licensed material involved, including kind, quantity, and chemical and physical form; and

(ii) A description of the circumstances under which the loss or theft occurred; and

(iii) A statement of disposition, or probable disposition, of the licensed material involved; and

(iv) Exposures of individuals to radiation, circumstances under which the exposures occurred, and the possible total effective dose equivalent to persons in unrestricted areas; and

(v) Actions that have been taken, or will be taken, to recover the material; and

(vi) Procedures or measures that have been, or will be, adopted to ensure against a recurrence of the loss or theft of licensed material.

You should have some criteria for determining when radioactive materials are considered to be “lost” and a policy or procedure for trying to locate or account for the lost materials. Although it sounds silly to say so, it’s not always obvious when radioactive materials are actually lost. For example, the necessary files may not be accessible and the person with access may be on vacation, making it hard to locate a particular source. Is the source lost? Not necessarily, if you can prove at some point that it was under control at all times – even if it takes a week or so for the custodian to return from vacation. On the other hand, you may decide a source is lost after only a few hours if you know exactly where it’s supposed to be and find it’s not there. You will need to decide for yourself when radioactive materials are considered lost, and you should be able to justify your decision to your regulators.

Your procedure should also include how you plan to determine dose to the public if the materials cannot be located or if it is determined they were discharged to the environment by, say, incineration or discharge into the sanitary sewer system. It’s acceptable to have the dose determination performed by an outside consultant if your organization lacks a full-time health physicist to perform these calculations, and hiring a consultant is a better idea than attempting them yourself and making a mistake.

If the missing radioactive are eventually located, this should be reported to your regulators immediately. Regardless of the outcome of your investigations and attempts to locate the missing materials, you will also need to document all your actions and the results of your investigation, and you should keep a copy of your report and all supporting documentation in your incident files.
Radiological terrorism
Dealing with radiological terrorism could be the subject of a full book in and of itself, and it is simply not possible to go into exhaustive detail in part of a single article. For this reason, only broad generalities will be given here.

In the event of radiological terrorism, your facility may be directly involved in the attack, or you may be called upon to provide support to the recovery efforts. In the latter case, your degree of participation will depend on your capabilities and whatever arrangements you may have made with emergency response personnel prior to the attack. In the absence of any pre-existing emergency response arrangements, you may not be permitted to participate directly in the emergency phase of the attack because the Incident Commander may simply not know what you and your staff can do. This means that, if you want to assist, you should work with local emergency responders in advance to determine your role, rather than simply appearing at the scene, meters in hand, wanting to help.

If an attack takes place on or near your facility, you may be directly involved. In this case, your highest priority will probably be protecting your personnel, recovering from any physical damage (fires, blast, etc.), and minimizing the spread of contamination to your facility. In general, a “dirty bomb” may cause extensive property damage, but there may be few, if any health effects from the radiological portion of the attack, although the radioactivity will complicate response efforts.

The scene of a radiological attack will have elevated levels of contamination and possibly radiation. It will also be a crime scene, it may pose serious non-radiological health risks, and emergency response efforts (putting out fires, stabilizing damaged buildings, isolating damaged utility lines, rescuing injured people, etc.) may be taking place. Obviously, rescuing people is the highest priority, along with addressing physical risks such as fires. But you must also remember that radiological concerns are also present, requiring setting up and enforcing radiological boundaries, surveying personnel leaving contamination areas, and performing radiation surveys as necessary to make sure that rescuers are not placing themselves at risk.

These guidelines are deliberately general because any terrorist attack or other incident will be unique. The best we can do is to try to keep these general guidelines in mind as we work with our regulators, emergency response personnel, and others involved in the incident to deal with the situation as it unfolds and presents itself.

Closing thoughts
Most radiological incidents are not life-endangering. Even terrorist attacks are likely to either inconvenience a lot of people or to endanger a few people due to radiation (although an explosion may, indeed, be deadly). In most cases, you will have the luxury of taking a minute to consider your actions and to think through your response so that you handle the incident appropriately. And remember, people must take the highest
priority – you can always decontaminate an area, but we can’t restore lost health or lives.

For more information:


Disaster Preparedness for Radiology Professionals, American College of Radiology, 2003 (available on-line at www.acr.org under “Disaster Planning Information” link)

Conducting a contamination survey (to accompany the spill procedure)

Performing radiation surveys can take a lot of time, but it is time well-spent because a hasty survey can lead to spreading contamination around your facility and off-site. Holding the detector too far away from the surface you’re surveying can give erroneously low readings, as can moving the detector too quickly. The phrase we use at the University of Rochester is “low and slow” – the detector should be help no more than about a half inch (1 cm) from the surface being surveyed and moved no more quickly than 1-2 inches per second (or 3-5 cm per second). While surveying, you should keep the audible response turned on because you will want to watch the probe itself – you don’t want to miss a spot, to hold the detector too far from the surface, or to contaminate the detector by bumping it into a contaminated surface. Listen to the count rate and, if you hear an increase, pause for a moment to see if the increase is sustained. If so, look at the meter face to see what the count rate is at that location.

When logging results, and in decontamination, you must convert from counts per minute (what the meter reads out in) to disintegration per minute (the amount of contamination present). This is done by dividing the count rate by the meter efficiency (which should be determined when the meter is calibrated). For example, if a geiger counter has 40% detection efficiency for P-32, a count rate of 80 cpm above background levels corresponds to a disintegration rate of 200 dpm (80 ÷0.4 = 200).
Radiological terrorism; general guidelines

We have established some general guidelines for responding to an-site radiological attack in a university or hospital setting. Some or all may be applicable to your facility.

1. Personnel who can neither hear nor see an explosion are probably not at risk. They should stay put if indoors or, if outdoors, go inside to await further information and instructions. People should NOT try to drive away because driving is likely to be more dangerous than staying put.

2. After going indoors, personnel should close open doors and windows, wash hands and face (take a shower if possible), and change your outer clothes if you can.

3. Contaminated injured people should have serious injuries treated without regard to contamination levels – contaminated persons do not endanger emergency response or medical personnel. If injuries are not serious, it may be possible to decontaminate the victims before transporting them, or at least to wrap them in a sheet or blanket to minimize the spread of contamination to vehicles and hospitals. This judgment call must be made on a case-by-case basis, depending on the extent of injuries and contamination.

4. You may need to perform surveys to establish radiological boundaries. These boundaries may be for high radiation or high contamination levels. According to regulations, the limit for removable contamination in an unrestricted area is 1000 dpm/100 cm$^2$ and radiation levels in uncontrolled areas cannot exceed 2 mrem in one hour. Radiation surveys are relatively easy to perform, and radiation boundaries can often be established fairly easily. However, contamination boundaries are more difficult to establish because contamination surveys can be difficult and time-consuming to perform. In some cases, it may be best to simply set contamination control boundaries a few hundred meters downwind and then expand or collapse them as you survey to confirm them. Note: Until you have a good idea of contamination levels, you should dress in contamination control gear (shoe covers, gloves, coveralls, for example) to reduce the risk of personnel contamination.

5. Potentially contaminated people should stay in the controlled area until they can be surveyed and released. If there are only a few people, it may be possible to survey everyone directly and decontaminate them as necessary. However, even a few tens of people who are contaminated can take a great deal of time to survey thoroughly and decontaminate. Depending on your capabilities and those of the emergency responders, you may have little option other than releasing moderately contaminated people with instructions on how to decontaminate themselves and their clothing. However, releasing such people should be a last resort, to be taken only when it is obvious that no other reasonable options exist and with the concurrence of regulatory and emergency response personnel.

6. Eating, drinking, smoking, chewing tobacco, applying cosmetics, and other possible avenues of accidental ingestion or inhalation should be prohibited in any radiologically controlled area, or by any potentially contaminated person.
How to choose a survey meter

<table>
<thead>
<tr>
<th>Type of radiation emitted</th>
<th>Example isotopes</th>
<th>Type of survey</th>
<th>Type of detector to use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha</td>
<td>U-238, Pu-238, Pu-239, Ra-226, Po-210, Am-241</td>
<td>Direct frisk, smear wipe</td>
<td>Zinc sulfide (ZnS) or proportional counter</td>
</tr>
<tr>
<td>Low-energy beta</td>
<td>H-3, C-14, S-35, Pu-241</td>
<td>Smear wipe</td>
<td>Liquid scintillation counter, proportional counter</td>
</tr>
<tr>
<td>Medium to high-energy beta</td>
<td>P-32, Sr-90, I-131</td>
<td>Direct frisk, smear wipe</td>
<td>Geiger counter, liquid scintillation counter, proportional counter</td>
</tr>
<tr>
<td>Low-energy gamma</td>
<td>I-125, I-129, Am-241</td>
<td>Direct frisk or smear wipe</td>
<td>Thin-crystal (1”x1mm) sodium iodide</td>
</tr>
<tr>
<td>Medium- to high-energy gamma</td>
<td>I-131, Cs-137, Co-60, Ir-192</td>
<td>Direct frisk or smear wipe</td>
<td>Thick-crystal (1”x1” or larger) sodium iodide, Geiger counter</td>
</tr>
</tbody>
</table>
Instrument use – radiological incident response
Spills

• **Stop spill**
• **Warn others**
• **Isolate the area**
• **Minimize exposure**
• **Stop ventilation if appropriate and possible**

• Start to clean up after immediate actions completed
Stop spill

- Pick up container (if possible) and place into bucket or deep tray
- Place absorbent materials over spilled liquid (or damp paper towels or rags over spilled powder)

- Idea is to stop adding more material to spill and to limit contaminated area
Warn others

- Call RSO or others who can assist
- Inform others nearby

- Idea is to keep unprepared people out of spill area and to get help in cleaning spill
Isolate area

- Put up physical boundary around spill
- Spill boundary should be at least 1-2 meters from farthest splash if possible
- May simply close and lock door to room
- ALWAYS put sign on spill boundary
- Nobody should enter spill area unless dressed in proper PPE
- Nobody should leave spill area until surveyed by RSO or trained rad worker (including personnel in area when spill occurred)
Minimize exposure

- Take a short time to think through the situation
- Make sure you are taking proper and reasonable actions
- Make sure you know how to deal with the situation
- Most radiological incidents are not life-endangering – you have the luxury of taking a few minutes to make sure you’re doing the right thing
Stop ventilation

- If spilled material is powdered or volatile, stopping ventilation can help to reduce spread of contamination
- Whether or not to try to stop ventilation is a judgment call on the part of the RSO or person at the scene
Clean-up

- Work from outside of spill area towards the center
- Work from top to bottom (if appropriate)
- Can usually use commercial cleaners (Formula 409, Windex, Easy-Off, etc.)
- Use Radiac Wash and similar products if you have radioactive metals

- Monitor area periodically to ensure
Skin contamination

• Contact RSO immediately
• Get good count rate on contaminated area and write it down for future reference
• Begin washing with mild soap and cool to warm water
• Count area every few washes to monitor clean-up progress
• May need to notify state, calculate skin dose, and/or monitor for internal exposure
High radiation levels

- Get good dose reading in area and in other “populated” areas (offices, etc.)
  - evacuate area if necessary
- Try to determine source of radiation
- Try to stop/shield source
  - Machines can be turned off
  - Sources must be either retracted or covered with shielding such as lead
Injured personnel in radiological incidents or emergencies

- Must treat each on a case-by-case basis
- Always make emergency responders or ER personnel aware of radiological concerns
- Even highly-contaminated patients pose very little or no risk to emergency responders or to ER staff
- Take care of most pressing problems first
- Examples:
  - Life-threatening injuries must be treated immediately
  - Mild injuries can sometimes wait for decontamination
  - Move injured personnel from dangerous radiation levels
When responding to incident:

- Choose appropriate detectors for expected types of radiation
- Take at least 1 backup instrument
- If situation is unknown, take GM, NaI, and ion chamber or micro-R meter
Appendix A: Glossary of Terminology

Activity: the number of nuclear transformations occurring in a given amount of material per unit time

\[ A = \frac{? \ m \ N_{(a)}}{W} \]

\( A = \) activity level in disintegrations/sec
\( ? = \) decay constant (units = /sec) = \( \ln(2)/t_{1/2} \)
\( m = \) mass of material present (units = grams)
\( N_{(a)} = \) Avogadro's number = \( 6.023 \times 10^{23} \)
\( W = \) atomic weight (units = atomic mass units)

Base: one of the four fundamental building blocks of DNA (A = adenine, C = cytosine, G = guanine, T = thymine); bases on opposite sides of the DNA molecule always pair up so that A is across from T and C across from G – this combination is called a base pair

BEIR: Biological Effects of Ionizing Radiation; a series of reports issued by a committee of the National Academy of Sciences

Bq (Becquerel): the amount of material that gives a disintegration rate of 1 disintegration per second - the Becquerel is the SI unit for activity level

\[ 1 \text{ Ci} = 3.7 \times 10^{10} \text{ Bq} \]

Ci (Curie): the amount of material which gives a disintegration rate of \( 3.7 \times 10^{10} \) disintegrations per second - a measure of activity; the Curie is the American unit for activity level

Codon: a group of three base pairs that codes for a single amino acid

Decay Chain (series): a series of isotopes resulting from the decay of a parent nuclide and its subsequent radioactive daughters to an ultimate stable form

Decay Constant: the fraction of the number of atoms that will decay in a unit interval of time

\[ ? = \frac{\ln(2)}{t_{1/2}} \]

\( t_{1/2} = \) isotope half-life

DNA: deoxyribonucleic acid, the primary genetic information molecule for all known life except for RNA-based viruses

Dose (absorbed): the energy imparted to matter by ionizing radiation per unit mass of irradiated material at the place of interest

\[ D = dr x t \]

\( dr = \) dose rate in mr hr\(^{-1}\)
\( t = \) time in hrs
Units of Dose: 1 rad = 100 ergs/gram in any material = $6.242 \times 10^7$ MeV g$^{-1}$
1 roentgen = $2.58 \times 10^4$ Coulomb kg$^{-1}$ of air
1 gray = 100 rad = 10,000 ergs g$^{-1}$ in any material

**Dose Equivalent**: the biological damage caused by the absorbed dose

$DE = D \times QF$

$QF =$ quality factor  
= 1 (beta and gamma radiation)  
= 3 (thermal neutron radiation)  
= 10 (fast neutron radiation)  
= 20 (alpha radiation)

**Dose Rate**: absorbed dose delivered per unit time (mr/hr)

**Gy (Gray – radiation dose)**: The SI unit of radiation dose; 1 Gray (Gy) = 1 Joule kg$^{-1}$ energy deposition from ionizing radiation

**Half-Life (effective)**: the amount of time required for radioactive material subject to multiple loss terms to have its activity reduced by 50% by a combination of radioactive decay and other losses.

$t_{1/2} (\text{eff}) = \frac{t_{1/2} (1) \times t_{1/2} (\text{rad})}{t_{1/2} (1) + t_{1/2} (\text{rad})}$

**Half-Life (radiological)**: the amount of time that is required for a radioactive substance to lose 1/2 of its activity

**Half-Value Layer (HVL)**: That amount of a material that is required to reduce the dose rate from a radiation source by a factor of 2

**Health Physics**: the profession devoted to the safe use of radiation and radioactivity

**Hormesis**: the presence of beneficial effects from exposure to an agent in small quantities, even if that agent may be harmful in large quantities

**IAEA**: International Atomic Energy Agency

**ICRP**: International Council on Radiation Protection (an international advisory body)

**Isotope**: atom of the same atomic number (containing the same number of protons) but with a different number of neutrons in the nucleus (different atomic mass) - can be stable or radioactive

**LNT**: Linear, No-Threshold; a hypothesis for radiation dose-response that suggests that all exposure to radiation is potentially harmful and the risk increases linearly with dose
**NCRP:** National Council on Radiation Protection and Measurements (a US governmental advisory body)

**Nuclide:** an atom characterized by the number of protons in its nucleus AND its energy level (ex: Tc-99m is a different nuclide than Tc-99, exhibiting a different half-life and different decay energies due to its existing in a different nuclear excitation (metastable) state

**Nuclide (parent):** the nuclide that exists prior to radioactive decay, decaying to form the progeny nuclide

ex: Xe-138 will B-decay to form Cs-138 therefore, Xe-138 is the parent nuclide and Cs-138, the progeny nuclide

**Nuclide (progeny):** the nuclide resulting from the radioactive decay of a parent nuclide (current terminology has replaced the term “daughter” with “progeny”)

**Radiation:** the emission and propagation of energy through space and/or through a material medium in the form of waves or, by extension, corpuscular emissions such as a or B particles

**Rad:** the deposition in any absorber of 100 ergs g\(^{-1}\) due to the absorption of ionizing radiation

**Rem:** exposure to that amount of ionizing radiation causing the biological damage equivalent to the deposition of 100 ergs g\(^{-1}\) in body tissue; the rem is the US unit for dose equivalent

**Radioactivity:** the property of certain nuclides of spontaneously emitting particles or gamma radiation following orbital electron capture, electron emission, isomeric transition, nuclear rearrangement, or spontaneous fission

**RNA:** ribonucleic acid; an information transfer molecule used in most cells, RNA is also the primary information-carrying molecule for RNA viruses

**Sievert (Sv):** exposure to that amount of an ionizing radiation causing the biological damage equivalent to the deposition of 1 J kg\(^{-1}\) in body tissue; the Sv is the SI unit for dose equivalent

**UNSCEAR:** United Nations Science Committee on the Effects of Atomic Radiation

**UV:** ultraviolet light; that portion of the electromagnetic spectrum that has a higher frequency and shorter wavelength than violet light; UV has three recognized wavelength bands, UVA (320-400 nm), UVB (290-320 nm), and UVC (<290 nm)
**Appendix B: Calculations and other useful information**

**The Law of Radioactive Decay**

\[ N_t = N_0 \times e^{-\lambda t} \]

\( N_0 \) and \( N_t \) are the number of atoms of a radioactive isotope originally and at any given time \( t \), \( \lambda \) is the isotope’s decay constant and is equal to the natural logarithm of 2 divided by the half-life of the isotope, and \( t \) is the elapsed time between the two measurements.

**The Law of Radioactivity**

\[ A = \lambda N \]

This can be combined with the Law of Radioactive Decay to produce the following:

\[ A_t = A_0 \times e^{-\lambda t} \]

**Radiation attenuation due to shielding**

\[ I_{sh} = I_0 \times e^{-\left(\mu / \rho \right) x} \]

**Radiation dose from a point source**

\[ D_2 = D_1 \times \frac{r_2^2}{r_1^2} \]

where \( D_1 \) and \( D_2 \) are the radiation dose at distances \( r_1 \) and \( r_2 \), respectively.

**Radiation dose from a line source**

\[ D_2 = \frac{D_1}{r_1} \times \left( \tan^{-1} \frac{L_1}{r} + \tan^{-1} \frac{L_2}{r} \right) \]

where \( L_1 \) and \( L_2 \) are the distance from both ends of the line source to a perpendicular line extending to the measuring location.
Radiation dose from a disk (or plane) source

\[ D_2 = D_1 \times \ln \left( \frac{h^2 + r^2}{h^2} \right) \]

where \( r \) is the radius of the disk and \( h \) is the distance from the center of the disk. For an irregularly-shaped area an effective radius is calculated by determining the area of the source, dividing by three, and calculating the square root.

Radiation dose in air from radioactive material

\[ D = \frac{\Gamma A}{r} \]

where \( A \) is the source activity in Bq and \( D \) is the dose rate in mSv/hr

### Dose conversion factors and risk factors for selected radionuclides

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Ingestion Dose Conversion Factor* (mrem/µCi)</th>
<th>Inhalation Dose Conversion Factor+ (mrem/µCi)</th>
<th>Risk Factor (µCi⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^3\text{H})</td>
<td>0.064 (whole body)</td>
<td>0.064 (whole body)</td>
<td>3.84 x 10⁻⁸</td>
</tr>
<tr>
<td>(^{14}\text{C})</td>
<td>2.09 (whole body)</td>
<td>2.09 (whole body)</td>
<td>1.25 x 10⁻⁶</td>
</tr>
<tr>
<td>(^{60}\text{Co})</td>
<td>26.2 (lower large intestinal wall)</td>
<td>208 (lung)</td>
<td>1.57 x 10⁻⁵</td>
</tr>
<tr>
<td>(^{131}\text{I})</td>
<td>88.5 (thyroid)</td>
<td>54.5 (thyroid)</td>
<td>1.43 x 10⁻⁵</td>
</tr>
<tr>
<td>(^{40}\text{K})</td>
<td>18.6 (stomach wall)</td>
<td>12.3 (lungs)</td>
<td>7.46 x 10⁻⁶</td>
</tr>
<tr>
<td>(^{90}\text{Sr})</td>
<td>115 (bone surface)</td>
<td>1300 (lungs)</td>
<td>9.13 x 10⁻⁴</td>
</tr>
<tr>
<td>(^{99m}\text{Tc})</td>
<td>7.41 x 10⁻² (thyroid)</td>
<td>3.02 x 10⁻² (lungs)</td>
<td>1.98 x 10⁻⁸</td>
</tr>
<tr>
<td>(^{137}\text{Cs})</td>
<td>49.8 (whole body)</td>
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<td>(^{232}\text{Th})</td>
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<td>(^{235}\text{U})</td>
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<tr>
<td>(^{238}\text{U})</td>
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<td>(^{238}\text{Pu})</td>
<td>1890 (liver, bone surface)</td>
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<td>2080 (bone surface, liver)</td>
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</tr>
<tr>
<td>(^{241}\text{Am})</td>
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<td>2.62 x 10⁵ (liver, bone, gonads)</td>
<td>9.12 x 10⁻⁴</td>
</tr>
</tbody>
</table>

* This assumes maximum transfer fraction from gastro-intestinal tract to blood
+ This assumes lung residence time of years (most conservative estimate)
** The organ(s) named are the critical organs (the organs receiving the highest dose)

The dose conversion factor given is the dose to the whole body from nuclide uptake
Radiation units and conversion factors

A number of units are used in the radiation professions. These are used to measure rates of radioactive decay, the amount of radiation absorbed by an object, and the biological damage caused by exposure to radiation. Since the US is not yet on the metric (SI) system, there are at least two sets of values for each unit, and there are several obsolete units that, officially, are not used but that still appear. This sheet will give a brief description of these units, exact conversion factors from one to the other, and rough conversion factors (for initial estimates).

Prefixes: Both US and SI units use multipliers in front of units. For example, km stands for kilometer, where the “kilo” (or “k”) means 1000. A kg is 1000 grams, a cm is 0.01 meters, and so forth. These prefixes and the amount of multiplication or division they represent is:

<table>
<thead>
<tr>
<th>Prefix</th>
<th>Multiplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>multiply by 1 trillion (a thousand billion)</td>
</tr>
<tr>
<td>G</td>
<td>multiply by 1 billion</td>
</tr>
<tr>
<td>M</td>
<td>multiply by 1 million</td>
</tr>
<tr>
<td>k</td>
<td>multiply by 1000</td>
</tr>
<tr>
<td>c</td>
<td>divide by 100</td>
</tr>
<tr>
<td>m</td>
<td>divide by 1000</td>
</tr>
<tr>
<td>µ</td>
<td>divide by 1 million</td>
</tr>
<tr>
<td>n</td>
<td>divide by 1 billion</td>
</tr>
<tr>
<td>p</td>
<td>divide by 1 trillion (a thousand billion)</td>
</tr>
</tbody>
</table>

Radioactivity

Radioactivity is a measure of the rate at which atoms decay by emitting radiation. It is NOT a measure of weight or mass – one ton of depleted uranium has the same decay rate (the same level of radioactivity) as one gram of radium-226. Radioactivity is measured in terms of disintegrations per minute.

Note: if you are using a radiation meter, you will almost always measure fewer counts per minute than there are disintegrations per minute. This is because virtually all detectors miss some of the radiation given off, so the count rate (what the instrument “sees”) is less than what the material emits. For example, if you are spraying somebody with a hose, only a part of the water coming out of the hose nozzle will hit that person).

SI: 1 Becquerel (Bq) gives a disintegration rate of 1 disintegration per second (dps)

US: 1 Curie (Ci) gives a disintegration rate of 37 billion dps. So 1 Ci = 37 billion Bq (37 GBq).

Roughly speaking, 1 Bq ≈ 30 pCi
1 MBq ≈ 30 μCi
1 GBq ≈ 30 mCi
Radiation dose (and dose rate)
Radiation dose measures the amount of energy deposited in an object by ionizing radiation. This is important because this energy deposition is what can cause DNA damage that may be harmful. We speak of radiation dose in air, water, human tissue, and many other objects – as long as an object is absorbing energy, it is receiving radiation dose.

One of the first units of radiation exposure is the Roentgen (R), which measures how much electric charge is generated in air by ionizing radiation. The Roentgen is now considered an obsolete unit and isn't used much anymore, although you can still find references to it.

1 R = exposure to that amount of radiation in dry air at standard temperature and pressure that generates an electrical charge of 2.58 * 10^-4 Coulomb/kg

SI: 1 Gray (Gy) = deposition of 1 Joule of energy per kilogram of absorber

US: 1 rad (r) = deposition of 100 ergs of energy per gram of absorber

Conversions:
1 Gy = 100 rad
1 mGy = 0.1 rad
1 rad = 0.01 Gy
1 mrem = 10 μGy
1 R = 0.87 rad (in water or tissue)

Dose equivalent:
Some kinds of radiation are inherently more damaging than others because of the physical properties of the radiation. For example, alpha particles are heavy and have a relatively high electrical charge and cause more extensive damage to DNA than beta particles do, even with the same amount of energy deposition. So depositing 100 ergs per gram of energy from alpha particles is more damaging than depositing 100 ergs per gram of energy from beta particles. Because of this, each type of radiation has what is called a “quality factor” (also called “relative biological effectiveness) that ranges from 1 to 20 or more. Multiplying the absorbed dose (see above) by the quality factor for a given radiation will give the equivalent dose in units of rem or Sieverts (Sv). Or, mathematically, Sv = Gy x QF.

<table>
<thead>
<tr>
<th>Radiation type</th>
<th>RBE (or QF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma</td>
<td>1</td>
</tr>
<tr>
<td>x-ray</td>
<td>1</td>
</tr>
<tr>
<td>beta</td>
<td>1</td>
</tr>
<tr>
<td>alpha</td>
<td>20</td>
</tr>
<tr>
<td>neutrons</td>
<td>5-20</td>
</tr>
</tbody>
</table>
Conversions:
1 Sv = 100 rem
1 rem = 0.01 Sv
1 μSv = 0.1 mrem

Dose rate
Radiation dose rate is a measure of how quickly radiation is depositing radiation in air, water, our bodies, or any other absorber. Dose rate can be measured in terms of absorbed dose or dose equivalent and in whatever units of time are most convenient. So, for example, some measure dose rate in mrem per hour and others in terms of mGy per year. Since the units of time are the same in SI and US units, it's only necessary to convert the units of dose mentioned above.

A radiation dose rate of 1 mrem per hour (1 mrem/hr) will give a person a radiation dose of 1 mrem in an hour. Since there are a total of 2000 hours in a working year (50 working weeks of 40 hours per week), working every day in a radiation field of 1 mrem/hr will give an annual dose of 2000 mrem (or 2 rem/yr or 20 mSv/yr). There are also about 8766 hours in a calendar year, so living in a background radiation field of about 15 μrem/hr will give you a dose of 131 mrem/yr from background radiation.

Conversion factors:
1 mSv/hr = 100 mrem/hr = 0.1 rem/hr
1 nSv/hr = 8.8 μSv/yr = 0.88 mrem/yr
    roughly speaking, 1 nSv/hr ≡ 1 mrem/yr
1 rem/hr = 10 mSv/hr
## Dose conversion factors and risk factors for selected radionuclides

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Ingestion Dose Conversion Factor* (mrem/μCi)</th>
<th>Inhalation Dose Conversion Factor+ (mrem/μCi)</th>
<th>Risk Factor (μCi⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>0.064 (whole body*)</td>
<td>0.064 (whole body)</td>
<td>3.84 x 10⁻⁸</td>
</tr>
<tr>
<td>14C</td>
<td>2.09 (whole body)</td>
<td>2.09 (whole body)</td>
<td>1.25 x 10⁻⁶</td>
</tr>
<tr>
<td>60Co</td>
<td>26.2 (lower large intestinal wall)</td>
<td>208 (lung)</td>
<td>1.57 x 10⁻⁵</td>
</tr>
<tr>
<td>131I</td>
<td>88.5 (thyroid)</td>
<td>54.5 (thyroid)</td>
<td>1.43 x 10⁻⁵</td>
</tr>
<tr>
<td>40K</td>
<td>18.6 (stomach wall)</td>
<td>12.3 (lungs)</td>
<td>7.46 x 10⁻⁶</td>
</tr>
<tr>
<td>90Sr</td>
<td>115 (bone surface)</td>
<td>1300 (lungs)</td>
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</tr>
<tr>
<td>99mTc</td>
<td>7.41 x 10⁻² (thyroid)</td>
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