Interpretation of Radiation Measurements

Continuing Education Lecture, CEL - 4
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Health Physics Society
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Baton Rouge, LA

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Misunderstandings abound when it comes to the interpretation of radiation measurements. There are two key factors governing such interpretations: 1) measurements have no meaning until interpreted and 2) measurements only have meaning in terms of how they are interpreted. Thus, recorded or reported radiation measurements have no inherent meaning by themselves, they are just numbers. Interpretation of radiation measurements may have as much to do with attitudes and perceptions of radiation risks as it does about technology. For example, a worker at an industrial facility observed the RSO taking readings with a Geiger counter and saw the meter go off scale. That was enough information for this worker to start an uproar that eventually involved several hundred other workers, the union, and management. Another worker at a food production facility heard a GM meter in use for surveying the installation of a new x-ray machine for product quality control. He raised concerns and when the company manager heard there was radiation in his facility, he told the x-ray company to remove their machine. This resulted in the loss of a $4 million sale for 20 x-ray machines.

Radiation safety specialists have the advantage for interpreting radiation measurements based on knowledge of comparative readings from background and other sources. Most people without this specialized knowledge do not know that we live in a sea of radiation which surrounds us all the time. Furthermore, a screaming Geiger counter may sound alarming, but radiation risks depend on many other factors, such as the type of radiation, the proximity of people, and the duration of exposures. A Geiger counter reading is only one piece of information which specialists would use for assessing potential risks.
The interpretation of radiation measurements may have as much to do with attitudes and perceptions of radiation risks as it does about technology. The very same measurement may have a wide variety of meanings to different people. For example, a technician at a nuclear plant saw a small blip on the readout of a whole body scan of a worker and announced, “Wow, we have a hot one here!” While the blip was technically interesting, although of no health significance, the worker heard the result as a matter of life and death. Litigation followed which cost the nuclear plant over $1.5 million for defense. Many times concerned persons have concluded that if radiation is measurable, it must be bad. Interpretation of the measurements becomes a matter of responding to fears of radiation. One person defending their conservative decision said, “Why take chances?” While this may seem prudent as a matter of the “precautionary principle – better to be safe than sorry,” such decisions could not be technically defended in terms of potential risks from radiation. Much more information is needed for interpreting radiation measurements for determining health risks.

I propose that there are two key factors governing interpretation of radiation measurements: 1) measurements have no meaning until interpreted and 2) measurements only have meaning in terms of how they are interpreted. Thus, recorded or reported radiation measurements have no inherent meaning by themselves, they are just numbers. Radiation safety specialists have the advantage for interpreting radiation measurements based on knowledge of comparative readings from background and other sources. Most people without this specialized knowledge do not know that we live in a sea of radiation which surrounds us all the time. Furthermore, a screaming Geiger counter may sound alarming but radiation risks depend on many other factors, such as the type of radiation, the proximity of people, and the duration of exposures. A Geiger counter reading is only one piece of information which specialists would use for assessing potential risks.
How Good do the Measurements Need to Be – What Quality is Defensible?

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Presentation at the Health Physics Society Midyear Meeting
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Specialists in radiation measurements, especially in a laboratory, tend to want to continuously improve the quality of their measurements. While this could be an admirable goal, the question of how the measurement may be used for decision making may be lost. For example, if you have a decision criterion for swipes of 2,000 dpm per swipe, does it really matter if a result is 20,000 dpm or 200,000 dpm? While these results differ by an order of magnitude, they will both lead to the same decision, namely to clean up. Another example has to do with minimum detectable activity (MDA). Do you need an MDA of 50 or 100 dpm when your action level is 2,000 dpm?

Sometimes it seems that measurements take on a life of their own, independent of the intended use of the data. Samples may be collected haphazardly (such as swipes) and the quality of the measurement exceeds the quality of the sample. Some of the factors affecting quality of measurements include: calibration conditions, energy dependence, factors affecting ion chambers and GM detectors, operator judgments, background interference, backscatter and self absorption, geometry, and wrong detector or wrong probe. Other variables include sensitivity of instruments, counting time, size of the signal, uniformity of samples, sample location, sample selection bias, sample preparation, and weight and volume errors.

Most importantly for measurement quality is that radiation is a random phenomenon, standards are uncertain, and background varies. Thus, all radiation measurements are at best only “best estimates.” How many significant figures are warranted by the uncertainty of the measurement? Most often the reported significant figures exceed the quality or defensibility of the measurement. This may lead decision makers to reach conclusions that are not defensible.
The Psychology of Radiation Measurements

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Charleston, SC       February 8, 2011

Good and defensible radiation measurements require several steps: 1) deciding what to measure (contamination or exposure), 2) choosing the proper instrument for the intended measurement, and 3) using the instrument properly. Assuming you have accomplished these three steps appropriately (there are countless pitfalls in these steps), you now have measurements to interpret. Several questions now arise: 1) what do the numbers mean, 2) are the measurements defensible, and 3) how much would you be willing to commit for resources on the basis of these measurements? This is where the psychology of radiation measurements could become very significant. Interpretation of radiation measurements may have as much to do with attitudes and perceptions of radiation risks as it does about technology.

The very same measurement may have a wide variety of meanings to different people. For example, a technician at a nuclear plant saw a small blip on the readout of a whole body scan of a worker and announced, “Wow, we have a hot one here!” While the blip was technically interesting, although of no health significance, the worker heard the result as a matter of life and death. Litigation followed. A worker at an industrial facility observed the RSO taking readings with a Geiger counter and saw the meter go off scale. That was enough information for this worker to start an uproar that eventually involved several hundred other workers, the union, and management. An industrial hygienist seeing Geiger counter readings above background on a granite countertop told the homeowner that she would not have the granite in her house. A fireman observing Geiger readings of twice background, called for cordonning off and evacuating several blocks of a city during a business day.

A common aspect of each of these scenarios is the assumption that if radiation is measureable, it must be bad. Interpretations of measurements become a matter of responding to fears of radiation. One person defending their conservative decision said, “Why take chances?” There are two axioms on measurements, 1) measurements have no meaning until interpreted and 2) measurements only have meaning in terms of how they are interpreted”
Emergency Response Plans – How Fears May Affect Reality*

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Consider the following four situations: 1) Fire fighters responding to an alarm in an office building, where radioactive density gauges were stored, noticed a GM detector appearing to read two times background. They subsequently evacuated several office buildings during a workday. Later they determined that the GM reading was within normal variations. 2) On a Saturday evening in December a man discovered a metal tube (bearing a radiation label) in an antique chest that he had purchased that afternoon. A 911 call resulted in evacuation of all families within a quarter mile on a cold winter night. About three hours later, the tube was found to be empty. 3) A vehicle incident on the Washington DC beltway included a labeled package that appeared to be damaged and leaking. Upon observing this, a State trooper and an ambulance driver evidenced symptoms of nausea and were taken by helicopter to a hospital for treatment. 4) After two days of radiation emergency response training, a fireman concluded from what he had learned that now he would not automatically run from potential radiation, he would just walk very fast.

What do each of these situations have in common? I suggest that in each case, fears surpassed reality. While we can all agree that good planning for emergency response is important, we may not realize that our best plans may be forgotten when responders make decisions regarding radiation safety. Because of the prevailing mindset about deadly radiation, responders may quickly revert to their basic instinct and decide to run, pull back, evacuate, or even neglect life-saving actions. When responders panic, what should we expect everyone else to do? For many responders the magic number is 2 mR/hr. At this exposure level, they will likely set up a barrier and evacuate everyone at higher levels. How, then does anyone ever reach levels recommended for sheltering such as 100 mR/hr or 1,000 mrem in two days? I suggest that we may have large differences in understanding among radiation professionals who develop radiation emergency response plans and those at the front line with responsibilities for public safety who may react from fears rather than reality.

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Is Your Radiation Instrument Telling you What you Think it Is?

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Since radiation does not give us any physical sensation, we have to rely on radiation instruments to tell us what is happening. Thus, we turn on a radiation instrument and look at the reading as a basis for making decisions for safety. The challenge at this point is to determine if the instrument is telling us the truth. There are at least twenty pitfalls that can affect the quality of radiation measurements. Several questions to consider, include:

1) Have we chosen the appropriate instrument for the type of radiation and safety decision which we want to make?

2) After choosing an instrument, how do we know if it is working properly?

3) After verifying operation, are we prepared to use the instrument properly (the way it was calibrated)? Assuming we have answered these questions appropriately, we then proceed to gather measurement data. The next question has to do with evaluating the quality of our measurement data.

4) What do these measurements mean and are they defensible?

5) Do these measurements support expensive decisions for safety, such as evacuation, clean up, or other actions?

The Ionizing Radiation Committee has presented a PDC on radiation instruments to answer these questions for the past two AIHce’s and also for 2012. The 2011 PDC was rated 8 out of 58. The instructors (authors of this article) have more than 60 years of radiation instrument experience. The focus of the PDC is not about theory or math, but rather about practical things to know about radiation instruments to allow industrial hygienists to do their jobs well and stay out of trouble. We will briefly review the fundamentals of radiation to better understand how instruments work and what they measure. We will bring a variety of radiation instruments to the PDC and pass them around to allow attendees to see how they respond to several exempt quantity
radioactive sources. Our mode of instruction is primarily show-and-tell, including a laboratory exercise for everyone to observe which instruments are fast or slow, stable or erratic, more or less sensitive, and analog versus digital readouts. The following are some of the topics and points we will discuss during the PDC.

Choice of Instruments for Exposures. Before choosing an instrument, you first have to decide on your purpose for making a radiation measurement. For example, are you wanting to determine someone’s external exposure to gamma radiation or x-rays? If so the first choice could be a standard or pressurized ion chamber. These are the only instruments that give a true reading of exposure (transfer of energy through the air) in milliroentgens per hour (or microSieverts per hour). All other instruments with roentgen scales are surrogate or secondary measurements. This does not necessarily mean they are not acceptable, as long as you understand their limitations. Standard ion chambers are slow, erratic, not very sensitive (not able to measure normal background radiation), and may be affected by air pressure (altitude) or temperature. Pressurized ion chambers are more sensitive, but only if the signal has a high enough energy to penetrate the heavy walled pressure chamber. For example, part of any x-ray signal will always have energies at 50 keV or below and most of this signal will not be measured by a pressurized ion chamber. The rule-of-thumb is that the bulk of an x-ray signal will have energies at about 1/3 of the applied voltage in the direct beam. Scattered x-rays, which we measure for safety decisions to protect people nearby, will have lower energy.

Radioactivity or Contamination Measurements. If you want to measure radioactivity (or activity,) then you should choose an instrument which will give the best response for the type of signal (alpha, beta, or gamma). The most common instrument for beta and gamma activity measurements is a Geiger-Mueller (GM) detector. There are several designs for GM detectors. The most sensitive design is called a pancake GM (a heavy metal housing of about 2 inches in diameter and ¾ inch thick). About 1/3 as sensitive is an end-window GM (a metal tube usually about 1 inch in diameter and about 5 inches long). Even less sensitive is a sidewall GM (a metal or plastic tube usually 1 inch in diameter and about 4 inches long). The least sensitive is the internal GM (tube about ½ inch in diameter and 2 inches in length. This design is the least sensitive because of its small size and because it is located internally within the meter base housing (thus, it will not detect any beta or low energy x-ray (below about 50 keV)).

The pancake and end window GM detectors are most sensitive to beta particles. If you want to measure beta radiation, either of these GM detectors could be a good choice.
However, if you want to measure gamma radiation, the beta sensitivity could be a problem. Since all gamma emitters also emit beta particles, you will always have a mixed signal unless the beta particles are shielded within a source capsule. Lack of understanding about the response of a pancake GM led to huge measurement errors a couple years ago when people were concerned about radiation from granite countertops. A person would hold a pancake GM probe in the air to measure normal background radiation (10 microroentgens per hour is a typical reading of gamma rays from the ground (terrestrial) and from outer space (cosmic)). The person would then place the GM probe on the granite surface and show readings of 500 microroentgen per hour. This measurement was then interpreted as 50 times above normal, often with a dramatic flare to imply danger.

There are multiple errors in this reading. When a GM probe is held in the air, it will only measure gamma radiation which can be interpreted as a true measure of exposure in microroentgens per hour. However, when the same probe is brought near a granite countertop, it will pick up beta radiation from the uranium decay products. Typical sources of naturally occurring radiation from uranium, radium, and thorium (found in all materials coming from the ground) will give a reading on a GM detector which is about 90% to 95% due to beta particles. There are two issues when a GM probe is responding to a beta signal. First, readings in roentgens per hour are only defined for ionization in air for x-rays and gamma rays. Thus, the transfer of beta energy cannot be measured in units of roentgen. Second, associating risk to beta particle exposure can be very misleading because beta particles do not travel very far in the air and do not penetrate into the body. Beta particle energy deposited mainly in the skin should not be interpreted in the same way as exposure to penetrating radiation to the whole body. The other error has to do with making granite surface measurements for estimating risks. Even when a person is in contact with the granite, the center of their body is typically 30 cm or one foot away. Thus, a better measurement for safety decisions should be made at a distance of one foot.

**Scintillation Detectors.** These detectors commonly use a crystal of sodium iodide (NaI) which converts gamma or x-ray energy into light photons. These photons are converted to an electrical signal through a photomultiplier tube and the signal is processed as a count rate for activity measurements. They are much more sensitive to gamma and x-rays than any other detector because of high density. High density means more electrons per unit volume and the corresponding higher probability that an incoming gamma ray will strike an electron and produce a signal. These detectors are also very
fast. The major limitation of scintillation detectors is that their response is highly dependent on the energy of the signal. Since all exposure reading instruments are calibrated in reference to the signal from cesium-137 (662 keV gamma), then all instruments (ion chambers, GM, or scintillation) should give the same reading for a cesium signal. However, for a signal with lower energy (which will always occur for x-rays), the scintillation detector could over respond by as much as a factor of 10 to 100. Conversely, at higher energies this detector could respond too low.

**Calibration and Energy Dependence.** Most people do not understand that exposure reading instruments are primarily only calibrated for a cesium signal. A radiation signal from any other source could give a very different response depending on how the instrument responds to different energies. Thus, if you do not know how your instrument responds to different energies and you do not know anything about the energy of the source, great errors could occur. Your instrument manufacturer should be able to tell you how your instrument will respond at different energies. It would be helpful to compare your instrument response with the anticipated energies which you wish to measure, so you can determine if your instrument is reading too high or too low. To account for energy differences for activity measurements the best option is to calibrate your instrument with the same source which you wish to measure.

**Geometry.** This has to do with the orientation of the detector to the signal. Since all radiation measurements are made by comparison, the best results are achieved by using the instrument in the same way it was calibrated. For example, a pancake GM probe is usually calibrated for activity measurements with a source positioned by a jig which holds the source at about ¼ inch from the face of the detector. Thus, all readings with this detector should be taken at a distance of ¼ inch. According to the inverse square law for point source of gamma radiation (doubling the distance reduces the signal by a factor of four), a reading taken at ½ inch is in error by 400%.

**Verifying Instrument Response.** When asked whether an instrument is responding properly, people often say when the instrument is on it clicks, or the calibration sticker shows that it was recently calibrated. Neither of these answers verify that the instrument is responding the same way it did at the time of calibration. The best way to verify response is to take a reading from a check source (ideally a source that will remain constant over a period of years) at the time of calibration. This check source reading should be recorded on the instrument calibration sticker. The normal steps to take before using a radiation instrument are: 1) check visually for any signs of damage to
the detector, cables, or meter housing, 2) verify the battery condition, and lastly 3) take a check source reading. The normal practice is to accept readings within 20% of the original reading.

**Interpretation of Measurements.** Assuming that you have chosen the proper instrument, verified that it is working properly and that you are using it the same what it was calibrated, and your understand the limitations of your instrument, you may now acquire measurement data. When interpreting these measurements, it may be helpful to know there are no absolute measurements for radiation. Since radiation is random in time and direction, repeated measurements will always differ and all radiation measurements are only “best estimates.” For evaluating the quality of radiation data, you have to consider, “What quality is needed for the particular decision to be made?” The standard practice assumes that portable radiation instruments should be accurate within 20% of the true value. If this seems high, consider the discussion above which describes several factors that could cause your instrument to be in error by several hundred percent. The basic rules before making an expensive decision based on portable radiation instruments are to ask lots of questions about how the measurements were made and as a minimum confirm the measurement by repeating (ideally with a different instrument or different people). This last caution can be problematic in an emergency where the first tendency is to take quick action for protecting people.

**Conclusion.** We conclude this article with two questions. Is your radiation instrument telling you what you think it is and is the measurement defensible as the basis for an expensive safety decision?
Data Quality Objectives – What Can Go Wrong?*

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Introduction

To make good decisions for radiation safety we depend upon portable or laboratory radiation instruments to tell us the type and the amount of radiation that may result in exposures. For the purpose of making “good” or “adequate” decisions, this chapter will encourage readers to consider the questions, “How good do the data need to be and what can go wrong?” This chapter is intended to provide practical introductory level guidance on matters that may affect data quality and interpretation of radiation measurements. You might consider this chapter as a practical engineer’s or decision maker’s view of the process for acquiring, interpreting, and defending radiation data. This chapter is not intended to include detailed theories on the principles of quality assurance. I will draw upon 40 years of experience working with radiation measurements laboratories, including 20 years as a laboratory director, almost 15 years as Chief of the Radiation Surveillance Branch with the U.S. E.P.A., and serving for eight years as QA officer for the EPA, Office of Radiation Programs. The material in this chapter also comes from extensive radiation instrument training which I have presented for 20 years to radiation safety officers, radiation workers, and first responders (Johnson 2000). Furthermore, this chapter draws extensively on material presented in Radiation Instrument Training: Six Challenges for Emergency Responders Chapter 15 of the textbook for the 2004 HPS Summer School on Public Protection from Nuclear, Chemical, and Biological Terrorism. (Brodsky, Johnson, and Goans 2004).

In addition, this chapter draws upon another very useful reference on quality of measurements, namely NUREG 1576, Multi-Agency Radiological Laboratory Analytical Protocols Manual, MARLAP, 2004. Readers are encouraged to read the three volumes (20 chapters) of MARLAP for a more comprehensive overview of data quality objectives than can be covered in this chapter. Appendix A, Directed Planning Approaches and Appendix B, the Data Quality Objective Process, for Volume I are particularly recommended for detailed discussions on data quality and measurement quality objectives. Additional references include Cember 1996, Knoll 1979, and Moe and Vallario 1992.

This chapter is intended to serve as an introduction to data quality objectives with an emphasis on what can go wrong. You may set data quality objectives with the best of intentions without realizing how many factors can go wrong which could lead to making inappropriate or non-defensible decisions for radiation safety. Over the years I have observed that people who specialize in radiation measurements, particularly in the laboratory, seem to focus on ever improving the quality of their measurements without considering how good the data need to be.

It seems as if the measurements take on a life of their own independently from the purpose for the measurements. For example, I see laboratory specialists going to great efforts to perform high qualify measurements for samples that are collected haphazardly. In other words, the quality of the measurement may far exceed the quality of the sample. This often applies to swipe samples which may be taken arbitrarily, with many sampling judgment factors that are taken for granted. I see requirements specified for minimum detectable activities (MDAs) that are far below action levels, and conversely action levels set below MDAs. Thus, quality requirements may be imposed on the measurements that have no meaning in regard to decisions at the action levels. I have heard measurement specialists lament that some data are no good for anything. I would suggest, however, that data within a factor of ten or more from the true value may be adequate depending on the quality appropriate for a particular decision. On the other hand, I often see radiation measurement data reported with four to six significant figures that absolutely cannot be justified.

Approach for this Review

This chapter will take a very pragmatic approach to the “Directed Planning Process” as defined by MARLAP. Namely,

“........a technically sound sampling and analysis design needs to balance the data user’s tolerance for uncertainty in the decision process with the resources available for obtaining data to support a decision.”

MARLAP also defines Data Quality Objectives (DQOs) as:

“Qualitative and quantitative statements that clarify the study objectives, define the most appropriate type of data to collect, determine the most appropriate conditions from which to collect the data (including sampling and analysis), and specify tolerable limits on decision error rates. DQOs should encompass the “total uncertainty” resulting from all data collection activities, including analytical and sampling activities.”

Establishing DQOs is a seven step process, including (see MARLAP, Appendix B):

1. statement of problem requiring radiation measurements
2. identifying the decisions for resolving the problem
3. identifying inputs to the decision
4. defining study boundaries
5. developing decision rules
6. specifying limits on decision errors, and
This review will consider factors that can affect quality of data primarily for portable instruments and only briefly for laboratory radiation measurements. I believe these two categories of measurements should be considered separately because of the greater inherent uncertainties of portable instrument measurements in comparison to better controlled conditions in laboratories.

**Quality of Portable Radiation Instrument Data**

A common rule of thumb for quality of measurements achievable by portable instruments is within plus or minus 20% from the true value (ANSI N323A-1997). Students often remark that this seems like a very large window of uncertainty. However, at best, calibration services typically will only certify that their calibrations assure that readings are within +/- 10% of the true value. This actually may be quite good considering that the ultimate basis of comparison for a calibration service (a National Institutes of Standards and Technology (NIST) traceable standard) is often uncertain by as much as 5%. Since the quality of a measurement cannot be better than the basis of comparison (calibration), then users of portable instruments really only have +/- 10% uncertainty to work with. The following discussion reviews some factors that can go wrong and cause that allowance for uncertainty to quickly dissolve before your eyes, including:

1. Have you chosen the right instrument?
2. How do you know if the instrument is working properly?
3. What is the proper or intended use of the instrument?
4. What factors may affect the response of your instrument?

**Which Instrument to Choose for a Particular Measurement**

Serious uncertainties can result from choosing the wrong instrument for a particular radiation measurement need. The first question that we should address is,

“*What is my need for radiation data?”*

What decisions for radiation safety or emergency response will require measurements of radiation? Ideally, choices on radiation instruments and probes should be governed by the decisions that will be made on the basis of radiation measurements. For example, are measurements needed for determining potential radiation exposures to workers or members of the public or are measurements needed to identify the extent of contamination (radioactive material) on the surfaces, equipment, or personnel? Choosing the best instrument for the job is a big factor in assuring that the best data are acquired for the necessary decisions. Unfortunately, people may find themselves inheriting instruments from a predecessor and then having to do the best they can with what they have. In some cases the inherited instruments may be marginally or even completely inadequate for the required decisions. For example, attempting to use an ion chamber to find a source of radiation, such as leakage from an x-ray machine or contamination on a surface may result in totally missing the signal. Also, a meter with an internal Geiger Mueller (GM) tube may not be the best choice for
measuring contamination on surfaces or clothing. I also audited a large x-ray radiography facility where operators for more than 15 years failed to detect backscattered x-rays in their control room because their internal GM instruments completely blocked the low-energy signal. They knew nothing about energy dependence of meter response and admitted that they had never seen the needle even wiggle on their detectors. For detailed discussions on best choices of instruments for particular needs, readers are encouraged to consider other HPS Summer School references (Johnson, 2001 and 2004). This references discuss 1) when to choose instruments for exposure measurements, 2) personnel exposure instruments (such as pocket ion chambers and digital dosimeters), 3) instruments for radioactivity measurements (including contamination monitoring, fixed or removable activity, 4) choice of instrument for low energy beta emitters, 5) choice of instrument for medium and high energy beta emitters, 6) choice of instrument for gamma emitters, 7) choice of instrument for alpha emitters, 8) choice of instrument for analysis of removable activity, 9) instrumentation for frisking, and 10) instrumentation for bioassay.

Verifying Instrument Operation

After choosing the appropriate radiation instrument, the next source of uncertainty has to do with whether the instrument is operating properly. When conducting audits, I always ask how people know if their radiation detector is working properly. Unfortunately, the answer often is that meter operation was verified during instrument calibration. There are several steps to verifying that a portable meter is operating properly or troubleshooting to determine what is wrong if it is not operating properly.

Battery Check. Usually the first step to verifying instrument operation is to turn the power switch to the battery setting and determine that the battery is adequately charged. Weak, discharged, or corroded batteries are the most common failure mode of portable instruments. Remove corroded batteries and attempt to clean the battery terminals with a flat blade screwdriver or a small wire brush. Clean the battery contacts as gently as possible to avoid damaging the contacts. Be sure the spring loaded contacts in the base of the meter are free to move. If the meter fails to respond to new batteries, then it may have a damaged circuit board or broken battery terminal connector from battery corrosion and it will need to be sent to a repair shop.

Check Source Response.* After determining that the battery reading is acceptable, you should verify the check source reading. Each meter should have available a relatively long-lived check source (with a half-life of four years or longer) preferably with an emission of the type and energy of radiation similar to the radioactive material to be measured. Check sources are usually small (one inch diameter) plastic buttons with a small amount of a particular nuclide that is exempt from regulations, thus no radioactive material license is needed. For example, for an alpha meter a good check source could be $^{210}\text{Po}$ or $^{241}\text{Am}$ (found in many smoke detectors). For medium/high energy beta probes, such as an end window or pancake GM, a good check source is $^{204}\text{Tl}$. For low energy gamma detectors, a good check source is $^{129}\text{I}$. For higher energy gamma or beta detectors, a good

* Note - Lack of a check source is one of the most common instrument deficiencies that I have noted in conducting radiation instrument training around the country. Often people believe that recent calibration is an adequate basis for assuming the instrument will respond properly. However, without a check source there is no way to verify instrument operation at the actual time of instrument use.
check source could be $^{137}\text{Cs}$. Gas lantern mantels (containing natural thorium) or orange glazed antique dishes (containing natural or depleted uranium) may also serve as good check sources.

After determining that the proper check source is available for the particular detector, the detector should be held in contact with the source and the reading compared with the corresponding reading recorded on the calibration form or on the sticker on the side of the meter. You should expect to get a reading close to the recorded value (within 10 to 20%) (ANSI N323A-1997). If you get a significantly lower reading or the meter does not respond, you should check to be sure you have the right check source for the particular detector. If you still get a low reading, it may be due to radioactive decay of check source. This could be a factor for $^{204}\text{Tl}$, which has a relatively short half-life of about 4 years. If the recorded check source reading is less than 1,000 cpm at the time of calibration, it should be replaced with a new source with a higher count rate.

**Possible Cable Failure.** If the check source is verified as suitable, but the probe still does not respond, the reason may be cable failure. Check that the cable is attached tightly to both the meter base and the probe. Also check the cable for visible signs of damage, such as broken insulation which may occur usually at the cable end fittings. If the cable appears sound and is tightly attached, check to see if the meter responds erratically when the cable is stretched or flexed. Often cables fail from internal damage that is not visible to the eye. If the meter still does not respond, or responds erratically, then replace the cable. Next to batteries, cables are the weakest component of portable survey instruments. It is always a good idea to keep an extra cable or two on hand for replacements. When ordering extra cables, be careful to specify the proper connectors for both the meter base and the probe. Survey meters customarily use either BNC or Type C connectors. Adapters to convert between the two connector types can be purchased if needed.

**Possible Probe Failure.** After replacing the probe cable, if you still get no response from the meter, it may be due to probe failure. First, check for obvious signs of probe damage. For instance, if the mica window is broken on an end window or pancake GM probe, then the probe will not function. If your NaI probe rattles, the photomultiplier tube could be broken. Dropping a NaI probe can easily break the photomultiplier tube. GM tubes are very susceptible to puncture fractures of the mica windows. For either of these types of damage, the probes can be replaced or repaired in a repair shop.

If there is no obvious indication of probe damage, the other way to check for probe failure is to replace the probe with one from another meter that you know is working. If the replacement probe works on your meter, that is a good indication of failure of the original probe. If the meter still fails to respond, that is an indication of meter base failure. Either probe failure or meter base failure will require repair in a meter repair shop.

**Exposure Meter Check Out.** The operation of exposure meters can be verified in a similar manner to contamination meters. The first thing to do is to verify battery condition and replace batteries or clean battery contacts if needed. Next, verify a check source reading with an appropriate check source. Useful check sources may be either a beta (for open window measurements) or a gamma emitter. A gamma source will be needed to check the response of an internal GM detector. It does not matter what the source may be as long as it results in a reproducible reading for verifying meter operation.
Factors for Proper Instrument Usage

After verifying that the instrument is working properly, the next challenge is knowing how to use it properly to acquire the needed data. Many new radiation workers think that using a radiation meter is simply a matter of turning on the power, pointing the instrument at the source of the radiation signal, and observing the needle or digital readout. It is much more involved. There are many factors that may cause a meter reading to be inaccurate and unacceptable (see the following section).

**Calibration Conditions.** Since all radiation measurements are made by comparisons with specific conditions of calibration, it is important to know the conditions of the meter calibration. Radiation measurement instruments are ideally calibrated for the specific nuclide and conditions intended for actual measurements. The closer the similarity between the conditions of calibration and use, the better the quality of the measurements. Conversely, any variations between use and calibrations conditions could increase the uncertainty of the measurement results. This means that a meter calibrated in reference to a $^{137}$Cs source (with gamma energy of 662 keV) will be most accurate when measuring $^{137}$Cs exposure or contamination. If the meter is used to measure another radionuclide with a gamma energy that is either much lower (100 keV) or much higher (1 MeV or greater), the meter may not respond in the same way as it did for $^{137}$Cs and the meter will read either higher or lower than it should. This variation in meter response with energy is called energy dependence (see the discussion later in this chapter for factors affecting instrument response). Preferably, a meter is either calibrated for exactly the same energies as will be measured, or choose an instrument that is designed to give a level response (in reference to the calibration source) over the range of energies that you will be measuring.

**Geometry Conditions.** When a meter is sent for calibration it is important to tell the calibration laboratory how the meter will be used. For example, most end window GM probes are calibrated for radioactive measurements with the mica window pointed at the source and held about 1/8 to 1/4 inch away from the source, often held sideways to the source. The orientation of the probe and source is called geometry and the best readings are achieved when the geometry of calibration and use are the same. To attain the best quality radiation measurements, either use the detector in the same way it was calibrated, or perform the calibration to match the intended use of the instrument.

**Factors Which May Affect Instrument Data Quality**

There are a number of factors that may affect radiation instrument response or the accuracy of the readings (Kathren 2001) (Moe and Vallario 1992). Some of the more common factors are listed below.

1. Calibration conditions
2. Energy dependence
3. Pressure, temperature, humidity
4. GM detectors – detector housing, window and thickness, resolving time, RC time constant, and speed of movement
5. Operator fatigue and noise
6. Background interference
7. Backscatter and self absorption
8. Geometry
9. Wrong detector or wrong probe

Some of these factors have already been discussed. However, the following section will provide more details on the main factors that could cause instruments to give inaccurate readings.

**Calibration Conditions.** As noted in the previous section, it is very important to know the calibration conditions of your radiation instrument. For the best quality results, the conditions of calibration and the conditions of use should be exactly the same (NCRP 1991). This means in particular:

1. calibration for the same nuclides or type and energy of signal as expected for actual measurements, and
2. calibration with the same orientation of detector to calibration source (geometry) as intended for the actual use of the instrument.
3.

**Exposure Calibrations.** A typical calibration range for exposure measurements uses a high activity $^{137}$Cs source to provide known exposure readings (mR/hr$^{-1}$) at varying distances from the source. The meter to be calibrated is placed on a movable trolley and centered on the cesium gamma beam. The exposure level in mR/hr$^{-1}$ is known for each unit distance from the source by a NIST traceable method. The meter is positioned at varying distances with known mR/hr$^{-1}$ to check the actual meter reading at two points on each decade scale of the meter. If the meter does not give the expected reading, an internal adjustment is made to bring the meter to the desired reading.

**Activity Calibration.** Meters are calibrated for radioactivity measurements by observing the meter response (counts per minute) to a standard source of known activity (disintegrations per minute). The procedure is very simple, but there are two factors that are especially important. One is that the known or standard radioactive source should be the same or very similar to the type, energy, shape, and size of the source that you wish to measure. The second factor has to do with geometry. The source and detector should be placed in a calibration jig that holds both in a fixed position. For example, the jig may hold the source in a position centered on the detector probe at a fixed distance of about ¼ inch.
**Energy Dependence.** Energy dependence has to do with how meters respond to an unknown source relative to the calibration source. Exposure meters are normally calibrated in reference to the 662 keV gamma rays from $^{137}$Cs. The question then is, how does a meter respond to either higher or lower gamma ray energies? Will your meter over or under respond at different energies? All meters should show a relative reading value of 1.0 at the $^{137}$Cs energy since this is the energy of reference. Some meters may over or under respond by 15 to 20 percent at higher or lower energies. Most people agree that they would rather have a meter over respond, rather than under respond. However, if a meter over or under responds by about 20 percent, that gives away all of the range of acceptable inaccuracy for only one factor, yet there are many additional sources of uncertainty in measurements.

**Ion Chambers (Window Open or Window Closed).** Opening the window allows better response for low energy gamma, however, when the window is open the meter may also respond to beta particles (Boag 1966). This introduces a dilemma, because when beta particles enter the chamber and cause ionization of the air, the meter will give a reading in response to the electrons released by ionization. The dilemma has to do with the read out units for ion chambers, which are in units of exposure or mRhr$^{-1}$. Exposure is only defined for ionization in air by x-rays or gamma rays. Thus, it is not appropriate to record readings for beta particles in units of mRhr$^{-1}$. To avoid this dilemma, there are two possibilities. One is to never open the window. Then the meter will not respond to any beta signal (also the window is usually closed for exposure calibrations and the best results are achieved by following the calibration conditions). The other possibility has to do with calibrating the meter for beta signals.

Sometimes it could be helpful to know how much energy is being transferred through the air from beta particles (Selby 1983)(Walker and Jacobs 1993). This may be done by taking readings with the window closed (gamma only) and with the window open (beta and gamma together). The difference between the readings is due to beta particles alone. However, to avoid the dilemma noted above, the reading attributed to beta particles will only have meaning if you know that the meter is calibrated for response to beta particles. Also, it is important to record the beta signal in units of absorbed dose (mradhr$^{-1}$) rather than mRhr$^{-1}$. Calibration for the beta signal will provide a correction factor to apply to the mRhr$^{-1}$ readings to convert to units of mradhr$^{-1}$.

**Energy Dependence of GM Detectors.** Many end window GM tubes will give a fairly flat or energy independent response from about 300 keV to 1,000 keV when readings are taken through the end mica window. However, at lower energies these GM tubes tend to drastically over respond by as much as 500 percent for energies from about 10 to 150 keV. Less over response is shown for the end window GM tube when read from the side of the tube rather than through the mica window. Unfortunately, the metal sides of the tube block out much or all of the signal below about 50 keV. GM tubes may be purchased with energy compensation to reduce the over response at low energies. Energy compensation is achieved by shielding to reduce the response to low energy gammas. Unfortunately, this results in the same loss of signal for low energies as described for readings through the side of an end window GM tube.

**NaI Energy Dependence.** Sodium iodide detectors for gamma rays are very energy dependent. Thus even small variations from the calibration energy of $^{137}$Cs may result in drastically different responses of the detector. In particular, the NaI detector may under respond by as much as 50
percent at the energy of cobalt-60 (1,170 to 1,330 keV). In contrast, at low energies (about 100 keV) the NaI detector may over respond by 1,000 percent (a factor of 10). Such a large over response could mislead decision makers into taking drastic actions that may not be warranted. Sometimes, the over response of NaI for low energies may be helpful. The over response by a factor of 10 at about 100 keV also means that the detector is extremely sensitive for low energy signals. Therefore, the NaI detector may be especially good for detecting or finding sources of exposures with a low energy gamma signal. Instrument users should be very careful, however, about recording exposure readings or basing response decisions on such readings. Instead, the NaI detector may be used to locate a signal, which is then quantified by an ion chamber as a true measure of exposure, without being affected by the energy of the signal.

**Pressure, Temperature, and Humidity.** Standard ion chambers and air proportional alpha detectors are very susceptible to the effects of pressure, temperature, and humidity. These detectors use chambers that are in contact with the air at normal atmospheric pressure. Humidity effects may be minimized by having the air entry to the chamber pass through a cartridge of silica gel to dry the air. This works fairly well for ion chambers, but does not work well with alpha air proportional counters.

Pressure and temperature affect the amount of air in the chamber according to the standard gas law. Since the chamber volume is also constant, the effects of temperature are directly proportional to pressure. Thus as the temperature of the air decreases, the pressure in the chamber decreases. As the pressure decreases the sensitivity of the meter decreases since there is less air in the chamber to intercept gamma rays. Therefore, there are two concerns for the effects of temperature and pressure. Ion chambers are normally calibrated at room temperature (about 70 degrees Fahrenheit) and they will respond with less sensitivity at lower temperatures. Consequently, ion chambers taken from a warm building for outdoor measurements at very cold temperatures will drastically under respond. Also, meters calibrated at sea level will show less sensitivity when taken to a higher altitude or conversely. The best way to minimize the influence of temperature and pressure is to calibrate and use the meters at the same temperature and altitude.

**Factors Affecting Data Quality for GM Detectors**

**Detector Housing.** Several factors can cause inaccurate readings with a GM detector. The first factor has to do with the construction of the GM tube. Side wall GM tubes with a metal housing will block all alpha particles and low to medium energy beta particles. When these solid metal GM tubes are installed internally in a hand-held meter, the casing will further block all beta particles and low energy x-ray or gamma ray signals.

**Window and Thickness.** End window and pancake GM tubes have a mica window that will allow detection of alpha, beta, and gamma radiation. However, mica is a fairly dense mineral that can absorb or block some or all of the radiation signal. Because the measurement of these three types of radiation is dependent upon a thin detector window to allow entry of the radiation into the detector, the effect of this window on the efficiency of measurement is considerable. Because of this effect, the NCRP recommends that instruments used for beta measurement be calibrated over multiple energy ranges from less than 300 keV, from 400 keV to 800 keV, and at energies greater than 1.5 MeV (NCRP 1991). This is amply demonstrated by observing the difference of efficiencies...
between $^{14}$C, $^{35}$S, and $^{32}$P, $^{90}$Sr which range from as low as 8% to as high as 32%. Because of loss of energy in the window, to detect alpha particles, it is necessary to bring the probe window to within about ½ to 1 inch from the source.

**Resolving Time.** GM tubes are able to achieve great sensitivity due to gas amplification of the signal. A single ionizing event from alpha, beta, or gamma results in release of a single electron. However, this electron is pulled so strongly to the anode that it collides with and knocks free a large number of additional electrons in what is called a cascade or avalanche. Out of this cascade ultraviolet photons set off additional cascades until as many as 100,000,000 electrons reach the anode. While these cascades are developing, however, if another ionizing event enters the GM tube, it will not be detected. The resolving time is the interval between two ionizing events where both will be detected. For pancake GM tubes, this interval is about 80 micro-seconds or 1.3 micro-minutes. While this is an extremely short interval, when events are occurring very rapidly (high count rate) much of the signal may be lost. For example, at a count rate of about 10,000 cpm, the counting efficiency is about 28 percent. However, as the count rate goes up, more and more of the signal is lost. At 500,000 cpm the efficiency is reduced to about 10 percent. Thus at this high rate, about 2/3 of the signal is lost. This means that a reading of 500,000 cpm should actually be about 1,500,000 cpm. If you know the resolving time (r) you can correct for the lost signal mathematically as follows:

\[
N = \frac{n}{(1 - nr)}
\]

Where 
- N = the corrected count rate (cpm)
- n = the actual meter reading (cpm)
- r = the resolving time (micro minutes)

The resolving time for a particular type of GM tube may be obtained from the manufacturer. You should know that a GM detector calibrated for exposure readings in mR/hr$^{-1}$ is also subject to resolving time losses. Manufacturers may try to compensate for such losses by adjusting the scales of the instruments.

**RC Time Constant.** While GM tubes appear to respond very quickly, the circuitry that allows detection of ionizing events or pulses takes a finite time to function properly. A typical pulse counting circuit is a combination of resistors (R) and a capacitor (C). Pulses are counted when the voltage across the circuit at equilibrium is proportional to the rate at which pulses are occurring. Many meters have an external switch that allows choices of the resistor in the pulse counting circuit. The switch has two positions marked “F” and “S.” These letters stand for fast and slow. In the fast position the meter responds more quickly, but the circuit takes 10 to 15 seconds to reach 90 percent of equilibrium. In this position the quick response may result in erratic meter movement (either analog or digital display) at levels from 0 to 1,000 cpm. Choosing the slow setting will result in a more stable meter reading, however, the meter responds slower and it takes as much as 30 to 45 seconds to achieve 90 percent of equilibrium. At levels above 1,000 cpm, the meter readings may be relatively stable in either the fast or slow setting, although you still have to allow the appropriate time for equilibrium before recording a reading. Since GM detectors are often used for frisking or
finding contamination, it is desirable to keep the switch in the fast setting to assure the fastest meter response. After detecting contamination, you could change to the slow setting for a more stable reading. Some meters may not have a switch to choose the response time. For such meters, wait at least 15 to 30 seconds before recording a meter reading.

**Saturation.** Some older GM detectors when turned on in a very high radiation field (such as 10 R/hr) may not respond. This is called saturation. Essentially the ionization in the GM tube is so intense the circuitry cannot handle the signal. The result is that the meter reads zero or near zero when in fact the exposure field may be dangerously high. To avoid saturation, the standard of practice is to always turn on the meter in an area of known low exposure and then proceed to the higher exposure area while watching the meter readings increase.

**Operator Judgment Factors that Affect Data Quality**

**Monitoring Technique and Speed.** The technique (speed of probe movement) during a survey using portable instrumentation can have a significant effect upon whether or not contamination is detected. If the movement of the probe is too slow, the maximum sensitivity (with respect to speed) is obtained but the area surveyed may be so small that an effective survey program may not be completed. If probe movement is too fast, large areas can be quickly covered, but sensitivity suffers to the point that significant contamination may be missed.

It is essential that a proper balance of speed and sensitivity be obtained to maximize both sensitivity and area coverage. The magnitude of the effect is dependent upon many factors and has been examined in detail within two publications: Minimum Detectable Concentrations with Typical Radiation Survey Instruments for Various Contaminants and Field Conditions (NUREG-1507) and MARSSIM (EPA 1997).

Speed of probe movement by itself will affect the ability of the instrument to detect contamination due to the characteristic electronic response (RC time constant) of the instrument. Typical speed of probe movement is between: 1) 0.5 m per second for wide area wheel mounted scanning probes used on floors and large surfaces to 2) perhaps 5 to 15 cm per second for a typical field/laboratory survey. As an example, the ability to detect contamination of 500 dpm/100 cm² using an alpha scintillation probe starts at over 90% for probe speeds below 5 cm per second and drops to less than 50% for a probe speed of over 10 cm per second. Probe size also makes a difference on speed and sensitivity. When the probe size (dimensions of the probe in line with the direction of scanning) drops to 5 cm, the probability of detection drops to less than 15 percent (EPA 1997). It is very obvious from the data that probe speed can defeat the intentions of the best calibrations and the calculated minimum detectable activities (MDA).

The choice of probe speed is very much a matter of operator judgment. I like to suggest that “People should fall in love with their radiation meter.” This translates into moving the probe quickly, but listening for an extra click that tells you to go back and take a slower reading. By this method, very thorough scanning coverage may be achieved quickly, without missing any contamination signal. Falling in love with your meter means becoming intimately knowledgeable of the ways your radiation meter may respond, in order that you can understand immediately what your meter is telling you about a radiation signal. This means you need to know intimately how the meter
will normally respond to a variety of radiation signals, what the meter is measuring, ways it could be misleading, and how to interpret the measurements as a basis for decisions or appropriate actions. For example, if you are a first responder, you need to know whether the meter readings warrant an expensive or drastic response action. You need to know whether the meter is telling you the situation is immediately dangerous (life threatening) to yourself or others that may be exposed to radiation. You need to know whether life saving actions are appropriate for care of victims. You need to know if the area should be restricted or evacuated.

**Thoroughness of Coverage.** Speed and thoroughness are related. When looking for point sources of contamination, even with slow scanning speed, but with wide loops of coverage you may entirely miss the contamination. For example, with a pancake GM probe, you essentially have to pass the probe directly over a point source to detect it. If you miss the source by even a half inch, then you may miss it entirely. What is the percentage uncertainty if you completely miss the source. Students often say 100%, but I would suggest that a missed source is infinite uncertainty.

**Fatigue.** When individuals are tired, they are less able to discern differences in the audible count rate of an instrument (they may miss that extra click). Another result of fatigue is boredom that may lead to apathy and inattention to detail. Tasks such as repetitive surveys of large areas may lead to apathetic fatigue. This may also happen when hours of surveying go by without detecting any signal above the normal background readings. It is essential to keep individuals motivated by rotating assignments so that this type of fatigue does not become a factor.

**Noise.** Since you often rely on an audible signal (increase in clicks) from a portable field instrument, the level of background noise can mask the ability to hear the increased count rate. In very noisy areas you may require a headset or ear pieces to discern changes in count rate. It has been noted that the use of a headset increased the ability of a surveyor to discern contamination by a factor of ten (EPA1997). Likewise, if surveys are being conducted in a quiet building, the surveyor may reduce the volume of the instrument to avoid disturbing or upsetting people in the area.

**Background Interference**

Background interference is the result of the signal picked up by the detector that is not due to the source or sample being measured (NUREG-1501). Usually the background signal is due to cosmic and terrestrial radiation, but it could be due to nearby sources in storage, or nearby contamination. Background interference primarily affects the smallest source signal that can be detected (the minimum detectable activity or MDA) (NUREG-1507). The MDA is directly proportional to the magnitude of background radiation levels. One might think of the background radiation level as analogous to a noisy area where the surveyor is attempting to hear an audible increase in count rate from a survey meter.

**Minimum Detectable Activity (MDA)**

It is very important to determine the background carefully in the area of desired measurements in order to assure detection of contamination or exposure that may occur at slightly above normal background levels. There are two types of errors to be avoided if possible (Altshuler and Pasternak
One is the mistake that a high background reading is due to the presence of a source. The other is to avoid mistaking a small source reading as a normal variation of the background signal. Allowing a five percent chance of making these two mistakes results in the following simplified calculation for the minimum detectable activity (MDA).

\[
MDA = 4.65 \sqrt{\frac{Bkg}{T} \cdot \text{Eff}}
\]

Where

- \(Bkg\) = background count rate (cpm)
- \(T\) = counting time (minutes)
- \(\text{Eff}\) = counting efficiency (%)

In this calculation it is crucial to know the background carefully. It is recommended that a thorough evaluation of instrument background be made at survey locations and the results of these surveys recorded and maintained. Prior to the conduct of each survey, a measurement of instrument background should be conducted and compared to stored values for a given instrument and physical location. When attempting to detect contamination, it is important to know what signal your meter will give in the absence of any particular source in the actual area of measurements.

Care should also be taken to evaluate MDA in relation to established action levels. In this age of ever increasing conservatism for radiation safety, we are prone to set very low action levels without realizing that our instrumentation may not be capable of quantifying the radiation at the action level which may be below our MDA.

For laboratory-based analyses, one should obtain samples (air, water, grass, vegetation, rain water, soil, urine, removable contamination smears, etc.) to establish the “environmental” background. In addition, samples of these representative media, as well as “blanks,” should be analyzed to determine the MDA. With this knowledge it will be possible to use accurate backgrounds to assist in establishing a more defensible and realistic MDA. A thorough discussion of the topics touched upon here can be found in: MARRSIM (EPA 1997) and, Background as a Residual Radioactive Criterion for Decommissioning (NUREG-1501).

**Backscatter and Self-absorption**

Backscatter is the result of beta particles or gamma rays reflecting from a surface back into the detector. When this occurs the detector will give a reading higher than it should. In effect the detector over responds due to backscattering. Backscatter is especially important when the materials are non-porous and of a high atomic number that facilitates the scatter of betas back into the detector medium. Self-absorption is an important consideration when lower energy beta emitters and alpha emitters are involved because the radioactive material may be imbedded in the surface of the material to be monitored. Self absorption results when beta or alpha particles are absorbed or blocked by the sample material. The self- absorption problem is by far more important than backscatter because it results in the underestimation of contamination.
These two factors play a part in both laboratory and field instrumentation calibration and efficiency calculations. In the laboratory, self-absorption is most important with low energy beta emitters, low energy photon emitters, and alpha emitters. In the measurement of high-energy beta emitters like $^{90}\text{Sr}$, self-absorption is not typically a severe problem. An increase in effective absorber thickness from 0 (just the detector face) to about 10 mg cm$^{-2}$ results in a count reduction of less than 10% for $^{90}\text{Sr}$, while an increase in 10 mg cm$^{-2}$ of sample thickness for a low energy beta or an alpha emitting radionuclide may result in an almost total loss of detection efficiency.

**Geometry Considerations**

When you send your meter for calibration it is also important to tell the calibration laboratory how you plan to use the meter. For example, most end window GM probes are calibrated with the mica window pointed at the source and held about 1/8 to ¼ inch away from the source. However, this same probe could be calibrated for exposure measurement, but for that purpose the probe is normally held sideways to the source. The orientation of the probe and source is called geometry and the best readings are achieved when the geometry of calibration and use are the same.

Instrument calibrations are performed on calibration ranges or using calibration jigs to assure reproducibility in the relationship of the source to the detector. A standard geometry configuration is important to assure that different instruments are calibrated under the same conditions to assure reproducible results.

Although geometry may be standardized for calibrations, instruments in the field may not be used in fixed “source to detector” geometry. In fact the geometry may vary during the same survey, and even more greatly with different instrument users. Also,

1. contamination found in the field is usually not homogeneous,
2. the contamination may not be the same energy as the calibration source, and
3. the surfaces present in the field may result in different backscattering than the calibration conditions.
4. You might be tempted to ask at this point “Why did I bother to calibrate the instrument in the first place?” The point of this review is not to cast aspersions on the calibration procedures, but to point out the many factors that may affect the response of the radiation instrument in ways that are different than the calibration conditions.

A typical pancake GM detector will have an efficiency of approximately 25-30% for $^{90}\text{Sr}$ in a standard calibration jig at approximately ¼ inch from a calibration source. If the detector position is raised by another ¼ inch or more above the source, the efficiency can easily drop to 10-15%. Considering that an individual may easily change the probe to surface distance during use in the field, the efficiency can be easily reduced to 5-10% or lower simply due to survey technique. For a point source, the inverse square law says that doubling the distance to source will reduce the reading by a factor of four. Reducing a reading by a factor of 4 is a 400% uncertainty. While surveying with a pancake GM probe, for example, it is hard to maintain a constant ¼ inch distance from surfaces just by eye.
When instrument surveys are conducted other “geometric” factors should also be considered. An example is the surface characteristics of the field source as compared to the calibration source, particularly for measurements using alpha monitoring equipment. When using ZnS, gas proportional, and air proportional counters, the surface “roughness,” dust, moisture content, and “probe covering” (used in an effort to prevent probe contamination) are highly influential. A slight covering of surface dust can completely mask significant contamination of an alpha emitter. Attempts made as a matter of practice to protect alpha scintillation and gas proportional equipment from contamination by bagging instruments in plastic makes the instruments completely useless. Similar and complete nullification of instrument effectiveness was observed at a remedial action site when alpha scintillation detectors were used to detect contamination on newly grassed and watered areas of park land. This same effect may occur in a building due to the washing and waxing of floors (which may cover up alpha contamination) or the good intentions of someone using a plastic cover over a GM pancake probe, alpha meter, or other instrument to prevent contamination or damage from sharp objects. This is one good reason to perform visual audits of survey meter technique, conduct extensive training, and have standard operating procedures that consider such factors.

Concern for reproducible geometry also means that you cannot monitor the ground or floors with a pancake GM probe by swinging the probe over the floor while holding onto the cable. This is actually bad practice for two reasons. First, it violates probe geometry (pancake probes are calibrated flat and parallel with the source) and secondly, carrying the probe dangling at the end of the cable will likely result in breakdowns in cable insulation and cable failure.

Geometry is also important for exposure meters. Depending on the meter design, the calibration beam may be directed at the bottom or side of the meter case. Again, the best quality readings are achieved by holding the meter in the same orientation, when taking actual readings, as the meter was held for calibration.

Wrong Detector or Wrong Probe

Depending on the characteristics of the radiation source, using the wrong detector or wrong probe could result in drastically over or under estimating the significance of the source. For example, I audited a large x-ray radiography facility recently where several internal GM meters were available to check for scattering and leakage of x-rays. The meters were carefully calibrated each year in reference to a $^{137}\text{Cs}$ cesium source. However, the x-ray operators admitted that they had never even seen the needles on their meters wiggle over a period of nearly 20 years of radiographic operations. My plastic scintillator showed easily measurable x-ray scatter in their x-ray control room and in a nearby manufacturing bay outside the radiography chamber. The x-ray operators never knew that their GM detectors would not measure any x-ray signal below about 50 to 75 keV. Since they were operating their x-ray machine at about 100 kVp, most of their x-ray signal (and especially scattered x-rays) would have been in the energy range of 10 to 30 keV. They also wore personnel dosimetry badges, but they stored their control badges together with worker badges in the control room. Thus, when the control badge readings were subtracted from the worker badges, they always came up showing no occupational exposure.

I have also done training for emergency responders at a military facility where their only instruments were internal GM detectors calibrated for exposure readings. They did not know that
these meters would not be suitable for contamination monitoring. Recently a student from a Federal facility brought an energy compensated pancake GM detector to the class. He did not know, and there was no indication in any of the literature with his meter, that his probe was calibrated with the signal entering the back of the probe (the side opposite the mica window) through the energy compensating shielding. In fact, his meter was equipped with a special holder that positioned the probe to read only from the mica window side. He also did not know that the energy compensation shielding on the back of the probe blocked all signals below about 80 to 100 keV.

While NaI detectors are very good for measuring gamma rays, many responders do not know that these detectors may badly over respond (by a factor of 10) to low energy gammas. Likewise, most GM detectors will over respond to lower energy gamma rays. When such detectors are equipped with energy compensation shielding (as noted above) the shielding may block a substantial part of the low energy signal.

Emergency responders can also make mistakes when making decisions about safety while using count rate instruments, such as a GM or NaI detector. Either of these detectors may give very high readings in terms of counts per minute (and the audio may be screaming), but drastic response actions may not be warranted. The reason is, for example, the signal may be due to beta particles which would result in little energy deposited in the body, especially at two feet or more from the source. Decisions on hazard response should ideally be based on exposure readings (mRhr⁻¹), preferably by an ion chamber or pressurized ion chamber that are not affected by the energy of the signal.

1. How to interpret the radiation measurements, and
2. How to evaluate or defend the quality of the measurement

In addition to addressing the challenges described above, this chapter will present a general overview of the most common types of instruments that first responders may need to know about, how these instruments work, and some of their limitations. This chapter will focus on useful information about portable and laboratory instruments for:

- Contamination monitoring
- Exposure rate measurements
- Personnel monitoring and bioassay

**Factors Affecting Data Quality for Laboratory Instruments**

**Laboratory Instrument Check Out**

Laboratory instruments are usually verified in a manner similar to portable instruments, although there are usually no batteries to check. The normal procedure when starting up radiation counting instruments in a laboratory each day is to run check source and background readings on each instrument. These readings are then compared, not to a single check source reading, but to a series of previous readings plotted as control charts (see the later section in this chapter for quality control of laboratory instruments).
LSC Quenching

Complications with LSC analyses may arise from chemical and color quenching. Quenching results from anything that interferes with the conversion of radiation energy into a light signal, or the transmission of the light signal to the photomultiplier tubes. Quenching results in a loss of the light signal produced by the scintillation media and a loss of counting efficiency. This loss of signal can cause the energy spectrum to shift to a lower energy channel (to the left) and can be severe enough to result in the complete loss of signal (when the light output is less than the electronics lower level discriminator). Physical absorption of the beta energy in the sample itself, or absorption of the light output by the sample, can also result in a reduced signal output. For example, when swipes are taken to check for contamination on a very dirty floor, the swipe may become completely black. This will physically block the light signal in the scintillation vial. Other factors can result in an increased light output (false activity), such as chemical or photoluminescence. Usually LSCs are designed to allow correction for quenching effects and to notify the operator of excessive quench or chemical luminescence. Thus, these problems are not typically severe.

Quench Correction. Because of variable effects of quenching, each individual sample may have a different detection efficiency in a LSC. Thus, converting the LSC reading in counts per minute to estimate the actual activity of a sample in disintegrations per minute requires a way to determine the counting efficiency for each sample based on the degree of quenching. The degree of quenching can be determined by means of an external standard. A quench calibration curve has to be developed for each nuclide of interest. This is done by preparing a series of samples (10 to 20) in the scintillation vials of choice. The same known amount of the nuclide (standard) to be analyzed is placed into each vial. The same scintillation mix is added to each vial. The first vial is then capped, shaken, and set in the LSC. Each subsequent vial then receives increasing increments of a quenching agent, such as carbon tetrachloride. The series of vials are then analyzed individually in the LSC by lowering each vial on an elevator into a light tight compartment. The LSC program then automatically exposes each vial to an external standard source (such as $^{137}$cesium) which gives a constant reading when no quenching is present. For vials with the increasing quenching agent added, the cesium source will give a lower reading proportional to the degree of quenching. Each vial is assigned a quench factor that can be related to counting efficiency. The plotted data of efficiency versus quench factor is called a quench calibration curve. This information is stored in the computer. Later when an unknown sample is run, it is first exposed to the cesium source to determine the degree of quenching (quench factor). The corresponding counting efficiency is then determined automatically from the stored quench calibration curve.

Interpreting Radiation Measurements

Part of the challenge for interpreting radiation measurements is to recognize that radiation is a statistically random phenomenon. Consequently, if a radiation measurement is repeated twice, ten times, or one hundred times, each reading may be different. This can be demonstrated in the classroom in several ways. First, turn on a GM meter and hold it in the air away from any known source. Ask the class to listen to the frequency of the clicks, which represents the background signal. Ask them to notice how many clicks they might hear in a ten-second interval. Then ask what that number might be if they repeated the exercise for several ten second intervals? As the students listen
to the clicks on the meter they will quickly realize that they are listening to random events. There are clearly groups of clicks together separated by short or long intervals without clicks. To further dramatize the randomness, you could ask if anyone could dance to that random beat? Once students recognize the randomness of the GM signal, it is important that you also ask them if that randomness is due to some artifact of the meter? They should understand that the randomness is due to the radiation signal and not the response of the instrument.

At this point, students may agree that radiation is a statistically random phenomenon, but they do not yet have any real world experience of what that means when conducting measurements. I like to provide that experience by a hands-on instrument exercise to demonstrate the variations not only with multiple readings on a check source by a single instrument, but also with repeated measurements with a variety of instruments.

**Hands-On Instrument Exercise**

This hands-on instrument exercise allows inter-comparison of 6 to 8 meters, all of which are calibrated to give exposure readings in units of mR/hr⁻¹. The meters include analog and digital ion chambers, a pressurized ion chamber, a NaI microR meter, a plastic scintillator microrem meter, a side wall GM probe, and a pancake or end window GM probe. Ideally this exercise would include instruments actually used by the students. This will then give them direct hands-on experience with their own specific equipment. Inter-comparisons of these meters provide students with the opportunity for hands-on observation of differences, in terms of response time, fast vs slow, stable vs erratic, sensitive vs not sensitive, readout variability, digital vs analog, size, weight, ease of use, etc. Each meter is used to read exposures at distances of 5, 10, 15, and 20 cm from a ¹³⁷Cs check source with an activity of about 20 microcuries. Thus, four readings are taken with each instrument as a basis for students to observe instrument response and to consider which meter they would choose, if they had to choose only one. Taking readings at four distances also allows students to observe the effect of distance. They are asked to determine if the inverse square law is verified by their readings, and if not, why not.

The exercise also includes one additional task. Namely, students are asked to convert all of the exposure readings into activity measurements. They are shown how to make this conversion by means of the exposure rate constant or specific gamma ray constant for ¹³⁷Cs. This illustrates the inter-relationship of exposure and activity units. This also helps students understand that a screaming count rate detector with a high cpm reading (10,000 to 100,000 cpm) does not mean that the exposure is high (the exposure in contact with the source is less than 1.5 mR/hr⁻¹).

After they have converted all of the exposure readings to activity units, students are then asked to determine their best estimate of the activity of the ¹³⁷Cs source, as a single number. They are not given any guidance on how to make this estimate. They usually have about 25 different data points to work with. Some of the meters, such as the microR meter and the NaI probe, read off scale at the 5 cm distance and therefore cannot provide data at that point. Also, the analog ion chamber gives essentially the same readings near zero mR/hr⁻¹ at 15 and 20 cm. The range of calculated activities is usually from about 6 to 14 microcuries due to variations between meters and the different distances.

Students are then asked to come up with a single number that they believe represents their best estimate of the ¹³⁷Cs source activity. Usually students will take a simple numerical average of all
data points to come up with a single number, although they sometimes throw out questionable data, and their best estimates cover a range of values. They are often reluctant to throw out any data points or to use any judgment on data selection. Sometimes, however, students will notice that two or three of the meters seem to give readings that are in close agreement and they will use only those readings for their best estimate. They may also notice that some of the readings do not follow the inverse square law and they may discard those data points. After students report their best estimate of the $^{137}$Cs activity, they are asked to explain their process and reasons for their answer. They are then shown how to use normal statistics for calculating the mean and standard deviation for their 25 measured data points. They are asked how would they determine the quality of their estimate if they had only one reading, which is the normal case in actual practice?

Such hands-on training provides the basis for students to choose the best instrument, to use it properly, and to defend the data acquired. It is pointed out that usually students may not have the benefit of multiple instruments, but only one. Therefore, they are also asked, if they had to choose only one of the various meters, which one would they chose and why? Quite often students will choose a digital meter over an analog. Somehow, the display of real numbers gives them better assurance of accuracy, compared to the swinging fluctuations of an analog needle movement. They usually dislike the slow response of ion chambers. They also tend to like the more steady readings achieved with scintillation detectors.

How to Evaluate or Defend the Quality of the Measurement

As students report their best estimate of the activity of the unknown source above, they are also asked about defending the quality of their reported estimate. They are asked if their data are an adequate basis for an important decision, such as evacuation or other life saving measures. They are asked about how much man-power or money should be committed on the basis of their measurements. Do they have enough confidence in their data to make expensive or life-determining commitments?

What Quality is Needed? I like to ask people to think about what quality of data is needed. The response is usually that the quality needed has to do with the purpose of the measurement. At this point I like to suggest two axioms on interpretation of radiation data:

1. Measurement results have no meaning until interpreted for a particular purpose
2. Measurements only have meaning in terms of how they are interpreted.

Acceptable quality is a function of what decisions or actions may be based on the radiation measurement. Thus, if a measured value is far below a designated action level, it may not matter if the is in error by a factor of two or more. For example, if the action level for removal of contamination is 2,200 dpm / 100 square centimeters, and the measured reading is 200 dpm, then even if it is low by a factor of ten, it is still below the action level. Likewise if the measured reading is 50,000 dpm and it is high by a factor of ten, it is still above the action level and will lead to the same decision.
**Standard Deviation.** Students are then introduced to normal distributions by illustrating the results of measuring a source’s activity with 100 different instruments, or taking 100 readings with a single instrument. We show that 68 of the 100 readings should fall within a range of values on either side of the true value which corresponds to +/- one standard deviation and that 95 of the readings should be within a range of values that corresponds to +/- two standard deviations. Assuming the instrument was properly calibrated and properly used, then the mean of the 100 readings should be a good estimate of the true value.

Students are further shown how to estimate the quality of a single measurement, where one standard deviation can be estimated by the square of the total counts collected for a particular counting time. Since most laboratory instruments provide an output in terms of count rates, the students are shown how to estimate one standard deviation by the formula:

\[
\sigma = \sqrt{\frac{N}{T}}
\]

Where  
N = the sample count rate (cpm), and  
T = the sample counting time (minutes)

Also, since radiation measurements always include a background signal, the students are shown how to estimate one standard deviation to include the uncertainty of the sample count and the background count as follows:

\[
\sigma = \sqrt{\frac{N_{s+b}}{T_s} + \frac{N_b}{T_b}}
\]

Where  
N_{s+b} is the count rate of the sample plus background (cpm)  
N_b is the count rate of the background (cpm)  
T_s is the sample counting time (minutes), and  
T_b is the counting time for the background (minutes)

**Reporting Measurement Results**

**Indication of Uncertainty.** Once an estimate is made of the uncertainty of a sample measurement, the result must be reported in a way that makes the uncertainty clear. The normal method is to report the measured value +/- one standard deviation. Another option is to report the measured value and its coefficient of variation (CV). The CV is defined as one standard deviation divided by the measured value (multiplied by 100 to convert to percent).

**Significant Figures.** The reporting of measurement data also needs to consider how many significant figures to include. Some may find it difficult not to carefully report all six or eight digits that may come from the printout of a measurement instrument. However, it is important to consider how many significant figures can be defended. Since no measurement can have an uncertainty less than the original calibration standard (typically 5%), then reported values with more than two
significant figures may not be defensible. For example, a reported value of 10 (which is two significant figures) says that the uncertainty is +/- 1, i.e. the real value is not a 9 or an 11 (or it would have been reported as a 9 or an 11). A reported value of 10 +/- 1 therefore gives an estimated uncertainty of +/- 10%. However, if the value is reported with three significant figures, such as 10.0 (which says the real value is not 9.9 or 10.1), then the implied uncertainty is now +/- 1%. Since this is less than the expected calibration error, it cannot be defended.

Many sources of measurement uncertainty also need to be understood for interpreting radiation measurements. These include:

- randomness of radiation
- calibration (uncertainty of the reference standard),
- counting time,
- amount of radiation,
- background variations,
- geometry,
- uniformity of samples,
- sample selection bias,
- sample preparation errors, and
- volume or weight errors.

For a detailed analysis of the effects of each of these factors and others, readers are encouraged to read MARLAP 2004 and Kathren 2001. Normally, reported measurement uncertainties are only based on the randomness of radiation (called counting errors). They do not include all of the other sources of uncertainty. Therefore, when defending the quality of measurements, it is important to realize that reported measurements probably have much greater uncertainty than typically given with reported values.

**Defending the Quality of Reported Measurements**

Instrument users should be able to answer the question, *“How do you know if the data are any good?”* The defensibility of measurements that may be reported and used for expensive decisions should be a matter of concern for all who use radiation instruments. We have reviewed many factors that can go wrong and contribute to the reduced quality of measurements. These include using the right instrument or probe appropriate for the radionuclide and material being measured. The measurement instrument also has to be used properly. This usually means using the instrument in the same way it was calibrated, or conversely getting the calibration done in the same way that the instrument will be used. Once the choice is made for the proper instrument, and its proper operation has been verified, then results can be reported with an estimate of uncertainty based on the randomness of radiation. However, we should be able to address questions about all of the other sources of uncertainty and the normal standards of practice for minimizing their effects.

The accuracy of measurements (closeness to the true value) is verified by the evaluation of readings from known sources. The disintegration rates of standards, or the exposure rates of known sources, are usually verified by reference to the National Institutes of Standards and Technology (NIST). The reproducibility of measurements (precision) is verified by duplicate samples or split samples. Reproducibility can also be evaluated by repeating measurements of the same sample.
“A basic rule of practice is to never report a measurement value, especially one that may lead to expensive decisions, without confirming the value by at least one repeat measurement”.

In other words, do not make any significant decisions without first confirming the measurement. The primary basis for defensibility of measurement data is careful documentation of instrument calibration, and instrument operational verification and use procedures. It is also important to document all quality control measures for verifying precision and accuracy of measurements.

Quality Assurance and Quality Control

Laboratory instrument function is typically evaluated either daily or prior to each use. The evaluation of instrument function is accomplished by a background count and a constancy source check. It should be noted that the source used for the constancy check does not have to be NIST traceable, although the same source should be used every time for each instrument. The sources used should be able to detect changes in efficiency and energy calibration.

Since most laboratory instrumentation uses an amplifier and analog to digital converter, it is quite possible, and has been observed, that either the low or high energy calibration might be correct, while the other may have drifted sufficiently to result in non-detection of lower or higher energy photons from radionuclides that are indeed present. For example, a daily check of a HPGe detector system had been conducted for years with only a 60Co source (1,173 and 1,332 keV photons) for constancy and energy calibration. But it was discovered that the energy calibration for photons supposed to appear at the energy of 240 keV had shifted sufficiently to be missed. This points out the importance of instrument performance checks on a periodic basis at both the low and high energy regions. This holds true for NaI detectors and LSCs as well.

A daily background, and/or blank sample check should be run with each analysis group. This will help to identify changes in instrument background due to both electronic noise and background from stored sources or cross contamination of samples.

Control Charts

All of the quality control data are plotted on a control chart (which can be an Excel™ or Quattro Pro™ spreadsheet). Data are compared not to a single check source reading, but to a series of previous readings plotted graphically. With a little work, control charts can also be used: 1) to evaluate instrument performance according to action points such as ±2 and 3 standard deviations from the expected mean, 2) to identify departures from the expected range, and 3) to compensate for the radioactive decay of instrument check sources.
Summary and Conclusions

This chapter has attempted to provide a broad review of factors that can affect the quality of radiation measurements, especially for portable instruments. The information provided is intended for practical guidance for to help with choices of radiation instruments, verifying that it is operating properly, using it properly, knowing what may cause the meter to read inaccurately, interpreting the readings, and defending the quality of the measurements. Both portable and laboratory instruments were reviewed for contamination monitoring, exposure rate measurements. For reliable radiation measurements, the appropriate instrument should be used or the limitations of available equipment should be recognized. In particular, instrument users need to understand the importance of calibration conditions, energy dependence, and geometry on measurement results. The best radiation measurements are achieved by reproducing all of the calibration conditions as closely as possible. Instrument users need to know how to use check sources to verify the operation of their instruments. Instrument users should be especially careful about over interpreting radiation measurements. Before making any significant decision based on radiation measurements, the measurement should be repeated at least once for confirmation. Instrument users should also practice with their portable instruments so they will know how the instruments respond and what the readings may mean.

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DC. Feb 15-18, 1993. Available as NUREG/CP-0050, USNRC.
Interpretation of Radiation Measurements

Outline for this Presentation
- Steps for defensible measurements
- Interpretation may be more about attitudes and risk perceptions, than about technology
- Two axioms on interpreting measurements
- A few anecdotes about interpretations
- Interpretation as a response to fears
- Caution leads to “precautionary principle”
- Dealing with uncertainty
- Many factors can cause measurements to be misleading

Good Decisions for Radiation Safety
- We rely upon good measurements for type and amount of radiation
  - Big questions?
- Is our instrument telling us what we think it is?
- What can go wrong?
- How good do the data need to be?

Interpreting Radiation Measurements
- Radiation is a random event
  - Random in time and direction
- What does this mean for measurements?
- How do we determine the quality or uncertainty of a measurement?
- How good does the measurement have to be for a defensible decision?
- How much money are we willing to spend?

Defending Results
- How do you know if the data are any good?
- Right instrument, working properly, used properly, calibration, energy dependence, geometry?
- Report results with estimates of all sources of uncertainty,
  - Be careful of significant figures
- Always repeat for confirmation,
  - Before reporting or making expensive decisions

Caveats
- I am not foremost expert, but a translator of your expertise to RSOs, rad workers, responders
- How to avoid decisions that may not be warranted by the data, false positives
  - Be skeptical, ask lots of questions before decisions
- Should I be telling my students something different?
  - I may not use the correct terms
  - as defined by Dan Strom

Radiation Safety Counseling Institute
Practical Guidance
- What affects data quality?
- How to interpret measurements?
- Engineer’s view of process for acquiring, interpreting, and defending radiation data
- May set goals with best intentions
  - Not knowing what can go wrong.
  - That could result in inappropriate decisions

Goals for Measurements
- Improvements in quality
- May not consider how good the data need to be
  - What will data be used for?
- Measurements take on a life of their own
- Samples may be collected haphazardly
- Quality of measurement may exceed quality of sample
  - Example - swipes, wipes, or smears

Quality Requirements
- MDAs set far below action levels
- Action levels set below MDAs
- Quality requirements imposed without regard to decisions and action levels
- What quality is needed?
  - Within a factor of ten?
  - With 4 to 6 significant figures?

Steps for Defensible Measurements
1. Deciding what to measure?
   - Exposure (mR/hr) or activity (cpm)?
2. Choosing the proper instrument
3. Verifying instrument performance
4. Using the instrument properly
   - According to calibration?
   - If you have been careful with above steps,
     - There are still countless pitfalls
     - You now have measurements to interpret

Two Axioms on Measurements
1) “Measurement results have no meaning until interpreted for a particular purpose”
   - They are just numbers
2) “Measurements only have a meaning in terms of how they are interpreted”
   - The meaning is whatever people believe

Psychology of Radiation Measurements
- Interpretation may have as much to do with attitudes and perceptions as it does with technology
- Same measurements may have different meanings for others
- Examples:
  - Technician at nuclear plant, “We got a hot one here!”
  - Industrial worker saw GM meter go off scale
  - Granite counter tops
  - Firemen observing twice background
  - Screaming GM meter

Radiation Safety Counseling Institute
Common Aspect of Scenarios
- If it’s measurable, it must be bad!
- Interpretation of measurements is often a matter of responding to fears
- One person’s answer for defending conservative decision, “Why take chances?”
- Common mindset
  Measurement = “Deadly Radiation”
- Risks of NOT taking action
  – Fears, criticism, responsibilities
  – Making a mistake

Questions for Interpretation?
- What decision do you want to make?
- How good do the measurements need to be?
- What do the numbers mean?
- Are the measurements defensible?
- How much resources are you willing to commit on the basis of these measurements?
- What is the risk of making a mistake?
  – What if you act or do not act?
  – How will you be held accountable?
  – Possible litigation?
  – Upset workers? Union? Management?

Making Good Decisions
- How to avoid decisions that may not be warranted by the data, false positives
  – Be skeptical, ask lots of questions before decisions
- Repeat measurements for confirmation, with other people and other instruments ideally
- Typical when finding actionable levels
  – Most want to take immediate action
- No one wants to be criticized
  – For not taking action

Dealing with Uncertainty
- Most people do not want to deal with uncertainty, they want absolute values
- They typically do not ask questions to evaluate the data or to determine if the data are defensible
- Tendency is to assume all data are of high quality and suitable for making decisions
  – When the number is written down, it becomes reliable

Uncertainty in Measurements
- Radiation is statistically random
- Decay constant – \( \lambda = \frac{0.693}{T_{1/2}} \)
  – Probability per unit of time that a decay will occur
- There are no absolute measurements of radiation
- No measurement is a single value
- All are “best estimates”
- What is the best quality standard available from NIST?
  – Since all measurements are made by comparison, we can never be better than the standard

Meaning of Standard Deviation
- \( \mu \pm 1\sigma \) – 68.3%
- \( \mu \pm 2\sigma \) – 95.5%
- \( \mu \pm 3\sigma \) – 99.7%
Standard Deviation

- The standard deviation of a single radiation measurement is approximately the square root of the total counts observed
  \[ \sigma = \sqrt{N} \]
- e.g. for 2500 counts in 5 minutes
  \[ \sigma = \sqrt{2500} = 50 \text{ counts} \]
- Activity is 2500 / 5 = 500 cpm
- \( \pm 50 / 5 = 10 \text{ cpm} \)
- or 500 \( \pm 10 \text{ cpm} \) or 500 \( \pm 2\% \)

How Do We Quantify Uncertainty

Estimates based on variations of sample count rates and background

\[
\sigma = \sqrt{\frac{N_{s+b}}{T_s} + \frac{N_b}{T_b}}
\]

- \( N_{s+b} \) = cpm of sample + background
- \( N_b \) = cpm of background
- \( T_s \) = sample counting time
- \( T_b \) = background counting time

\( \sigma \) for 3 Day AC at 4 pCi/l

\[
\begin{align*}
N_{s+b} &= 161 \text{ cpm} \\
N_b &= 109 \text{ cpm} \\
T_s &= 5 \text{ minutes} \\
T_b &= 15 \text{ minutes}
\end{align*}
\]

\[
\sigma = \sqrt{\frac{161}{5} + \frac{109}{15}} = 6.3 \text{ cpm}
\]

Coefficient of Variation

\[
C_v = \frac{\sigma}{N_s} = \frac{6.3}{52} = 12\%
\]

\( \ast 4 \pm 12\% \) or \( 4 \pm 0.5 \text{ pCi/l} \)

Reporting Conventions

- 4.0 pCi / l (no indicator of uncertainty)
- 4.0 \( \pm 0.5 \text{ pCi / l} \) (uncertainty as std. dev.)
- 4.0 pCi / l \( \pm 12\% \) (uncertainty as CV)

Significant Figures?

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<th>CV - %</th>
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<td>( 1 \times 10^2 )</td>
</tr>
<tr>
<td>135</td>
<td>( 1 \times 10^2 )</td>
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Defending Results

- Ask lots of questions
- How do you know if the data are any good?
- Right instrument, working properly, used properly, calibration, energy dependence, geometry?
- Report results with estimates of all sources of uncertainty,
  – Be careful of significant figures
- Always repeat for confirmation,
  – Before reporting or making expensive decisions

Guidance - MARLAP Manual

- Multi-Agency Radiological Laboratory Analytical Protocols Manual
  – July 2004
  – Three Volumes
- NUREG-1576
- EPA 402-B-04-001A
- NTIS PB2004-105421

Directed Planning Process - MARLAP

“Technically sound sampling and analysis design needs to balance tolerance for uncertainty in the decision process with resources available for obtaining data to support a decision”

Data Quality Objectives - DQO

- Qualitative and quantitative statements that clarify study objectives
- Define types of data to collect
- Define conditions for collecting data,
  – Including sampling and analysis
- Specify tolerable limits on decision error rates
- DQOs should encompass “total uncertainty”

Seven Steps for DQOs

1. Statement of problem
2. Decisions to be made
3. Inputs to the decisions
4. Study boundaries
5. Decision rules
6. Limits on decision errors
7. Optimize the design

Portable Instruments

- Rule-of-thumb, $+/- 20\%$
- Calibrations may be within $+/- 10\%$
- NIST standard may be within $+/- 5\%$
- Allowance for uncertainty affected by:
  – Choosing right instrument
  – Is it working properly
  – Is it used properly
  – How does instrument respond
Choosing Right Instrument

- What is your need for data?
- Exposure or activity measurements?
- What decisions do you want to make?
- May have to rely on available meter
- Could be marginal or totally inadequate

Verifying Instrument Operation

- How do you know if your instrument is working properly?
- Battery check
- Check source response
  - Appropriate source?
- Possible probe or cable failure?

Proper Instrument Usage

- Calibration conditions
  - Reproduce calibration conditions
- Geometry conditions
  - How was meter calibrated?

9 Factors Affecting Quality

1. Calibration conditions
2. Energy dependence
3. Factors affecting Ion Chambers
4. Factors affecting GM detectors
5. Operator fatigue and noise
6. Background interference
7. Backscatter and self absorption
8. Geometry
9. Wrong detector or wrong probe

1. Calibration Conditions

- All radiation measurements are made by comparison
- Key Questions
  - Compared with what?
  - How is comparison made?
- Either use meter as it was calibrated or calibrate according to use
- What quality of reading do you expect from a portable radiation detector?
  - + / - what % from true value

Calibration Conditions

- Two types of calibrations
  - Exposure = mR/hr
  - Activity, dpm = cpm/Eff.
- Exposure calibration range
  - High activity Cs-137, 662 keV gamma
  - Position meter at varying distances from source for low to high mR/hr
- Activity calibration, EFF. = cpm/dpm
  - Use NIST traceable standard source for known dpm (typically +/- 5%)
2. Energy Dependence

- How does your meter respond to an unknown source relative to the calibration?
  - Ion chambers
  - GM
  - Nal

---

Energy Dependence

Bicron Ion Chamber

Nal and Plastic Scintillator Response

Thin Window – Thin NaI

Pressurized Ion Chamber Response
3. Factors Affecting Standard Ion Chambers

- **Pressure, Volume, Temperature**
  - Gas law, equation of state
  - Pressure affected by altitude, barometric pressure

\[
\text{Pressure} \times \text{Volume} = \text{Constant} = \text{Temperature}
\]

- **Humidity**
4. Factors Affecting GM

- Housing
- Window and thickness
- Resolving time
- RC time constant
- Saturation

5. Operator Judgments

- Monitoring technique
- Speed of movement
- Thoroughness of coverage
- Fatigue
- Noise
- Need to fall in love with your meter

Operator Factors

- Operator Judgments
  - Choice of detector? (what do you need to measure)?
  - How fast to move the probe?
  - How thorough to scan?
  - How close to the surface (geometry)?
- Operator fatigue
  - What happens to judgments and quality of readings when operator becomes tired?

Speed of Probe Movement

- How fast can you move the Probe?
  - Without missing the signal
  - If you miss the signal, what is % error?
- Balance between thoroughness and time available
- What will data be used for?
  - How important is the decision to be based on the data?
- In general, move at 1 – 10 cm / sec

6. Background Interference

- Unwanted signal
- Usually cosmic and terrestrial radiation
- Reduce background by shielding
- Determines MDA

Background Interference

- Normal background from cosmic and terrestrial radiation = about 5 - 10 \( \mu R / hr \)
  - Pancake GM - 50 cpm
  - Thin window NaI - 200 cpm
  - 3 in x 3 in NaI - 30,000 cpm
- Could be a nearby gamma source
  - May mask sample counts
  - Lower the background by shielding to improve sensitivity

Health Physics Society Midyear Meeting, Baton Rouge, LA  February 12, 2014
Interpretation of Radiation Measurements - CEL - 4

Minimum Detectable Activity
- The smallest activity capable of being detected at a given confidence level
  - Can you quantify your action level with confidence in your measurements?
- Typically, but not always, set at 95% CL
- By definition, 5% probability of being either a Type 1 or a Type 2 error

Logical Errors
- Type 1 Error
  - mistaking a high background count as a true sample count
- Type 2 Error
  - mistaking a low sample count as background

Detection Limit – LLD & MDA
Assumes \( N_{sb} = N_b \)
also 5% error in reporting activity when none is there
and 5% error in reporting no activity when activity is present

\[
\begin{align*}
\text{LLD} &= 4.65 \text{ sb} \\
\text{LLD} &= 4.65 \sqrt{\frac{N_b}{T_b}} \\
\text{LLD is in cpm} \\
\text{dpm} &= \text{cpm} / \text{Eff} \\
\text{MDA} &= \frac{\text{LLD}}{\text{Eff}}.
\end{align*}
\]

MDA
- Crucial to know normal reading on your meter in the absence of a specific signal
- Compare MDA to established action levels

7. Backscatter & Self Absorption
- Backscatter
  - Reflection of beta and gamma radiation back into detector
  - Causes over response
- Self absorption
  - Result of absorbing substance in path of radiation to be measured, eg. sample itself, air, walls or window of detector
  - Causes under response

8. Geometry
- Orientation of detector and source
- Best results when measurement reproduces calibration conditions
- Field conditions not usually homogeneous
  - May not have same backscatter
- For point sources, distance is crucial
  - Inverse square law
9. Wrong Detector or Probe

- Using wrong detector can result in drastic over or under response
- Problems with energy compensated GM
- Energy dependence of NaI

Wrong Probe or Detector

What do you want to measure?
- Use Ion Chamber when you know the source of radiation and want to measure exposure in mR/hr
- Use GM, NaI, Plastic, ZnS - for measuring activity, cpm
  - Use to find source

Factors Affecting Uncertainty in Radiation Measurements

- Radiation is random
- Variation in standards
- Sensitivity of instruments
- Counting time
- Amount of radiation
- Background and variations
- Geometry
- Uniformity of samples
- Sample location
- Sample selection bias
- Sample preparation
- Volume and weight errors

Radiation Measurements

- No measurement is a single value
  - If repeated, result will be different
- No absolute measurements
- Radiation quantities are determined by comparisons

What Quality of Data is Needed?

- What decisions or actions will be based on the data?
  - How expensive will be your decision?
- What is acceptable?

Interpreting Radiation Measurements

- Radiation is a random event
  - Random in time and direction
- What does this mean for measurements?
- How do we determine the quality or uncertainty of a measurement?
- How good does the measurement have to be?
- How much money are we willing to spend?
Defending Results

- How do you know if the data are any good?
  - Right instrument, working properly, used properly, calibration, energy dependence, geometry?
  - Report results with estimates of all sources of uncertainty,
  - Always repeat for confirmation,
  - Before reporting or making expensive decisions

Data Quality Objectives - Summary

“The best laid schemes o’ mice an’ men / Gang aft a-gley.”
“To a Mouse,” by Robert Burns

- We can set DQOs, but can we achieve them?
- How good does the data need to be?
- How many things can interfere?

9 Factors Affecting Quality

1. Calibration conditions
2. Energy dependence
3. Factors affecting Ion Chambers
4. Factors affecting GM detectors
5. Operator fatigue and noise
6. Background interference
7. Backscatter and self absorption
8. Geometry
9. Wrong detector or wrong probe

Summary

- Radiation is random
- No radiation measurement is a single value
- All are “best estimates”
- We can quantify uncertainty based on randomness of radiation
  \[ \sigma = \sqrt{\frac{n}{t}} \]
- More than one significant figure may not be defensible
- Be careful about your MDA

Common assumptions
- If its measurable - it must be bad
- Written data are always good
- Must take immediate action

Common to make decisions (cry wolf)
- Without verifying the measurement

Stay calm

As minimum – repeat at least once
- For confirmation, with other instruments and people, if possible

What do the numbers mean?
Measurements only have meaning in terms of interpretation
Data interpretation may be driven by fears
- Of radiation
- Of consequences, health risks, liabilities
- Making a mistake
- Is your interpretation defensible?
- What are you willing to commit?
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- BS - Civil Engineering, University of Vermont (1961)
- MS - Sanitary Engineering, Massachusetts Institute of Technology (MIT) (1963)
- PSE - Professional Sanitary Engineer Degree, MIT and Harvard University (1963)
- PE – Licensed Professional Engineer, Vermont (1965 – present)
- CHP – Certified Health Physicist, American Board of Health Physics (1983–present)
- FHPS - Fellow of the Health Physics Society and Past President (2000)
- President, American Academy of Health Physics (2013)
- Commissioned Stephen Minister – Counselor, United Methodist Church (2003–present)

Experience

2010 – pres. Director, Radiation Safety Counseling Institute. Workshops, training, and counseling for individuals, companies, universities, or government agencies with concerns or questions about radiation and x-ray safety. Specialist in helping people understand radiation, what is safe, risk communication, worker counseling, psychology of radiation safety, and dealing with fears of radiation and nuclear terrorism for homeland security.

2007 – pres. VP, Training Programs and consultant to Dade Moeller Radiation Safety Academy, training and consulting in x-ray and radiation safety, safety program audits, radiation instruments, and regulatory requirements.

1984 - 2007 Director, Radiation Safety Academy. Providing x-ray and radiation safety training, audits, and consulting to industry (nuclear gauges and x-ray), universities, research facilities, and professional organizations.

1988 - 2006 Manager and Contractor to National Institutes of Health (NIH) for radiation safety audits of 3,500 research laboratories and 2,500 instrument calibrations a year, along with environmental monitoring, hot lab and analytic lab operations, and inspections of three accelerators and over 100 x-ray machines.

1990 - 2005 President of Key Technology, Inc. a manufacturer and primary laboratory for radon analysis with over 1,500,000 measurements since 1985. Primary instructor at Rutgers University for radon, radon measurements, radiation risks, radiation instruments, and radon risk communication courses (1990-1998).

1986 - 1988 Laboratory Director, RSO, Inc. Directed analytical programs and Quality Assurance for samples from NIH, Aberdeen Proving Ground, radiopharmaceutical companies, and the nuclear industry.


Health Physics and Professional Activities


Publications