Ion Chambers:
Everything You've Wanted to Know (But Were Afraid to Ask)

by Paul R. Steinmeyer

Introduction

Ion chambers (short for ionization chambers) are gas-filled detectors, used exclusively for the measurement of exposure rate, and which differ greatly from all other types of gas-filled detectors (e.g., G-M and proportional detectors). Rather than detecting a series of pulses or counts which can then be equated to an exposure rate, radiation causes a current to flow in an ion chamber detector. The magnitude of this electric current is proportional to the exposure rate. It has no meaning, then, to talk about observing "counts" with an ion chamber.

Ion chambers are valuable for three qualities. First, they possess a relatively flat response to a wide range of gamma and x-ray energies (typically from 10 keV to nearly 10 MeV). Second, they are the best instrument for measuring high levels of radiation. Finally, they are capable of accurately discriminating between the beta and gamma components of a radiation field. Ion chambers are used widely in the nuclear power industry, but also have their place in medical facilities, industrial x-ray facilities, and in radiography.

Editor's Note: *This article, now out of print, has been one of the most-requested articles in our archive. It is presented here in an "encore" for the convenience of our readers.*

This article addresses only those portable, hand-held ion chambers commonly used in performing radiation surveys, although mention is made of pressurized ion chambers which are typically used for environmental monitoring applications.

History

Hand-held ion chambers were developed at the University of Chicago as a part of the Manhattan Project during World War II. They were designed to measure beta and gamma radiation fields during the experimentation with nuclear fission. Two designs were created and used, code named "cutie pie" and "juno." Both of these types are still marketed today, with updates in the electronics being the only substantive change.

The cutie-pie style is the type which looks like some sort of "ray gun," with the cylindrical ion chamber mounted on the front. The electronics package is equipped with a pistol-type handle, and legs are usually provided so that the cutie pie can be set up and left in place facing a radiation source. Figure 1 shows an Eberline RO-5 ion chamber, which is a modern ion chamber in the cutie-pie style. The juno style looks more like a "normal" radiation detector (i.e., a rectangular metal box) with the cylindrical ion chamber sticking out of the front. Figure 2 shows a Victoreen Model 471, which is a modern ion chamber in the juno style. Cutie pies and junos are, operationally, effectively identical. Caps can be removed from

Figure 1. *Eberline RO-5 Ion Chamber*

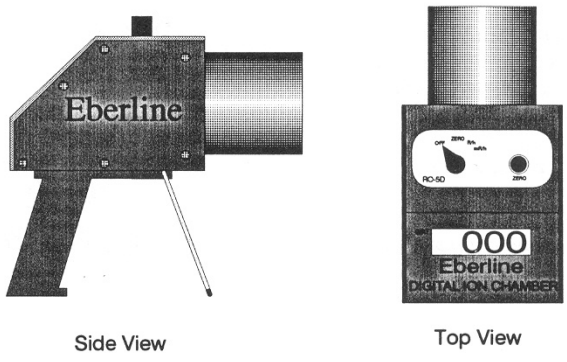
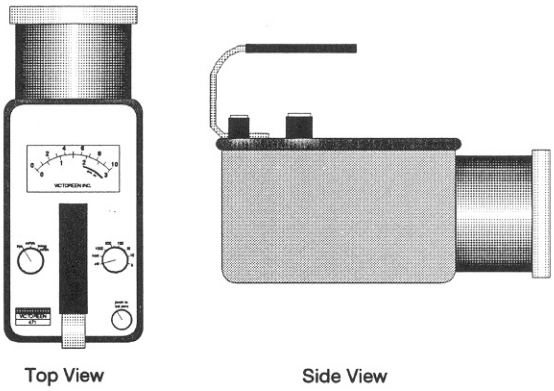


Figure 2. *Victoreen Model 471 Ion Chamber*



the fronts of these detectors to expose a thin window which allows the passage of beta particles. They are both designed to measure the radiation field coming from a specific source rather than the exposure rate in a general area. In other words, these designs are directional.

Most ion chambers used today have the detector contained inside a more "regular-looking" rectangular instrument case. The thin beta window faces down, and is exposed by opening a slide on the bottom of the instrument case. This style (which I will refer to as the "standard-package") is less directional than cutie pies and junos, and is thus more suited to making general area radiation measurements. Figure 3 shows a Bicron RSO-50E ion chamber, which has an internal cylindrical detector, and Figure 4 Shows a Ludlum Model 9 ion chamber, which has an internal rectangular-shaped detector. Both of these exhibit the standard-package style.

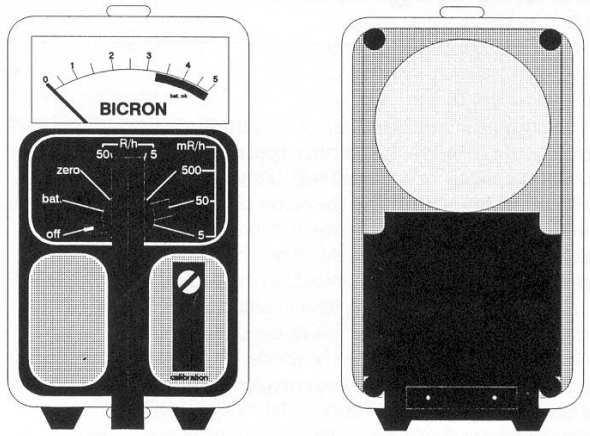
Operating Principles

Ionizing radiation produces ions in air (and all other matter) when the radiation interacts with it; the radiation "strikes" an electrically neutral air molecule and liberates an orbital electron. An ion pair is thus created consisting of the freed electron (negative ion) and the remaining molecule which is now positively charged (positive ion). This occurs around us constantly due to radiation from cosmic and natural sources. Normally, the positive ion will quickly recombine with a free electron, and the electron previously liberated will recombine with some other positively charged ion.

The fundamental unit of photon (i.e., gamma and x) radiation exposure, the roentgen (R), is a measure of the ionization of dry air. One R equals 2.082×10^9 ion pairs generated in 1 cm^3 of dry air at standard temperature and pressure. Stating this in terms of exposure rate, in a one R/hr radiation field, 2.082×10^9 ion pairs per hour are created. The number of ion pairs generated is also proportional to the energy of the original photon.

If a voltage were applied between two electrodes in an air-filled chamber, then the component parts of the ion pairs would be attracted towards the oppositely-charged electrode. The electrons (negative ions) would be attracted to the positive electrode (or anode)

Figure 3. *Bicron RSO-50 Ion Chamber*



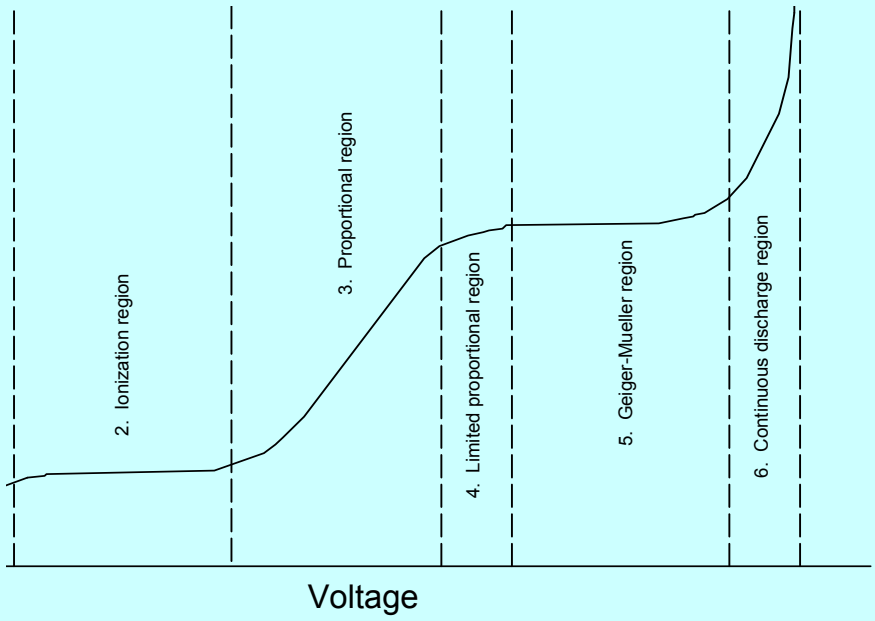
and the positive ions (remaining molecule) would be attracted to the negative electrode (or cathode). Since the positive ion is much, much more massive than the negative ion, the movement of the positive ion is very limited and can be ignored. An electrical current is then generated by the movement of electrons to the anode.

In an ion chamber, a volume of gas (usually air) is isolated inside an electrically conductive container, which is used as the cathode. The chamber is vented to the atmosphere through a desiccant which ensures that the air in the chamber remains dry. In the center of the detector chamber is an electrode (electrically insulated from the chamber) which is the anode. The application of a relatively low voltage to this chamber creates an electric field, which causes the ions to begin to flow and creates an electrical current. As the voltage is increased, a point will be reached where every negative ion generated will be attracted to and collected by the anode; this is called the saturation level (See Box, "The Six-Region Curve for Gas-Filled Detectors," on page 14). The saturation voltage required will increase somewhat for higher radiation levels. The trick is to keep the voltage high enough so that saturation is achieved, but low enough so that the proportional region is not entered. Figure 5 is a schematic representation showing the main component parts of a simple air-vented ion chamber. (Note that saturation voltage in an ion chamber is not related to saturation in a G-M detector. Use of the same word is coincidental.)

Electrical current, expressed in amperes, is a measure of the number of electrons which pass a given point in an electrical circuit in a unit time. One ampere equals 6.281×10^{18} electrons 2.082×10^{9} electrons generated in 1 cm^3 of dry air would generate a current of only 9.208×10^{-14} amperes for each cm^3 of chamber volume. For a typical hand-held ion chamber (detector volume of about 300 cm^3), a current flow of 27.62×10^{-12} amperes would be generated. This level of current is an exceedingly tiny quantity and difficult to measure accurately. This limitation is the reason why ion chambers are not usually used for measuring low (i.e., near-background) levels of radiation. A method used to overcome this limitation is to pressurize the gas in the chamber volume. The denser gas will have more interactions with the incident radiation, thus creating a larger current for a given quantity of photons. Pressurized ion chambers, however, have their own limitations which are discussed in the next section.

The Six-Region Curve for Gas-Filled Detectors

All gas-filled detectors detect radiation with different characteristics based on the relative applied voltage between the anode and the cathode. As voltage is increased slightly above zero, the recombination region is entered. In this region, the negative ions generated are slowly attracted to the anode. Most, however recombine with a positive ion before reaching the anode. Increasing the voltage further, the ionization region (or saturation region) is entered. In this area, all of the negative ions generated reach the anode. Ion chambers, which respond evenly to different energies of radiation, operate in this region of the curve. Relatively low efficiency and exceedingly small pulse height are characteristic of this region. The current generated by the ion flow (rather than individual pulses) are used as the instrument detection mechanism for ion chambers. As the detector operating voltage continues to be increased, the detector enters the proportional region (region 3), where pulse height is proportional to the energy of the photon or particle which initiated the pulse. Proportional detectors, therefore, can discriminate between different energies of radiation by analyzing the pulse height. As the detector operating voltage continues to increase, the limited proportional region (region 4) is passed through and enters into region 5, the Geiger-Mueller region. In this region all pulse heights are equal and efficiency is relatively high, although photon efficiency will vary based on energy. Finally, the continuous discharge region is entered where the voltage is so high that arcing occurs.



The Six-Region Curve for Gas-Filled Detectors

***Figure 4**. Ludlum Model 9 Ion Chamber*

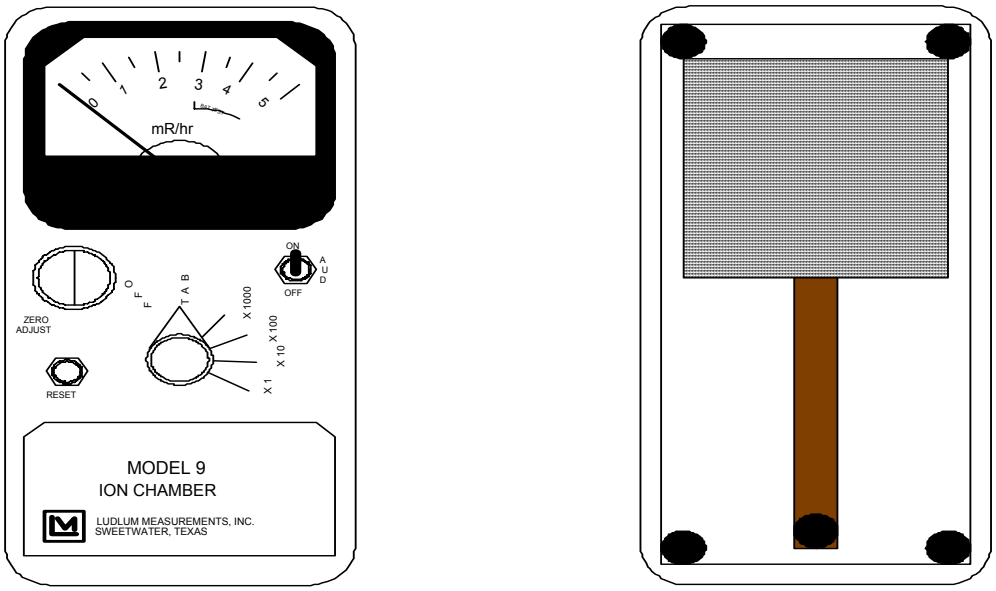
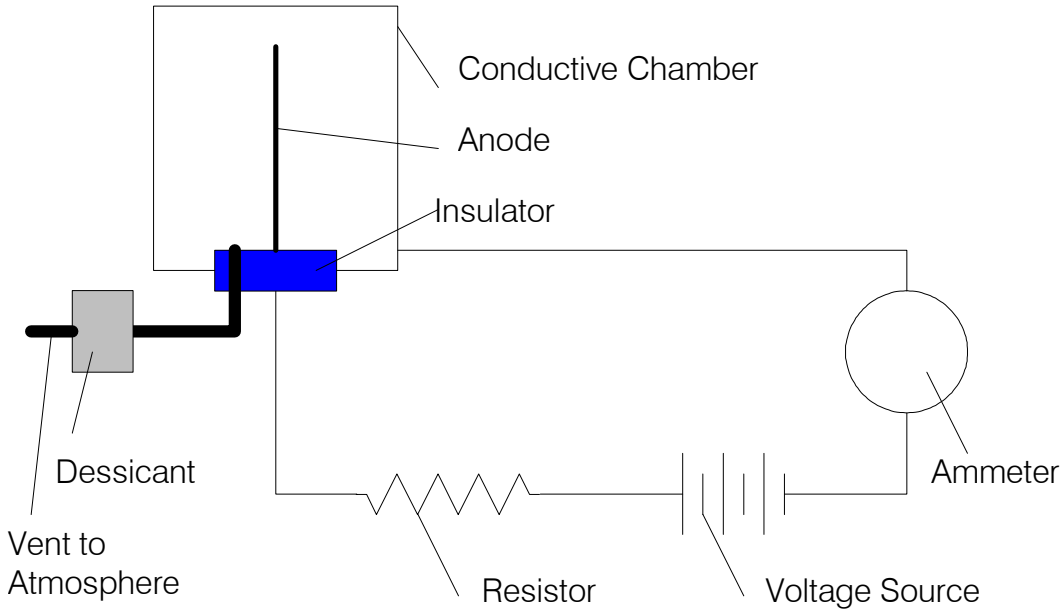


***Figure 5.** Schematic Diagram of a Simple Air-Vented Ion Chamber*



Construction

There are no real differences between cutie pie, juno, and standard-package types of ion chambers other than the shape, and that the standard package is less directional than the other two. The thickness of the chamber wall is made as uniform as possible over five sides so that the response to radiation is as even as possible through any side. The directionality of the cutie pie and juno types comes from the fact that the sixth side is effectively shielded from radiation by the instrument case and electronics package which is in *back* of the detector. Standard-package ion chambers have this shielded side on the top which compen-sates for the directionality. The thickness of the chamber wall (or chamber wall plus detector case wall) is made thin enough so that low-energy photons (e.g., 10 keV) can penetrate into the detection region.

Most commercially available hand held ion chambers use air as the detection gas because it's inexpensive and widely available. The air is vented through a desiccator to achieve the dry air quality required. The desiccant must be changed (or dried by heating) periodically to ensure proper operation of the detector. Changes in atmospheric pressure (or tempera-ture) affect density of air, and thus the "efficiency" of the ion chamber. Many ion chambers (especially high-precision ion chambers) come with a table for correcting readings to existing environmental conditions.

One end of the ion chamber has a thin window which is exposed by removing a cap or cup (cutie pie and juno types), or by sliding back a window on the bottom of the case. This allows beta particles into the detector for the determination of beta dose rate. All of the beta particles are effectively prevented from being detected when the window is covered.

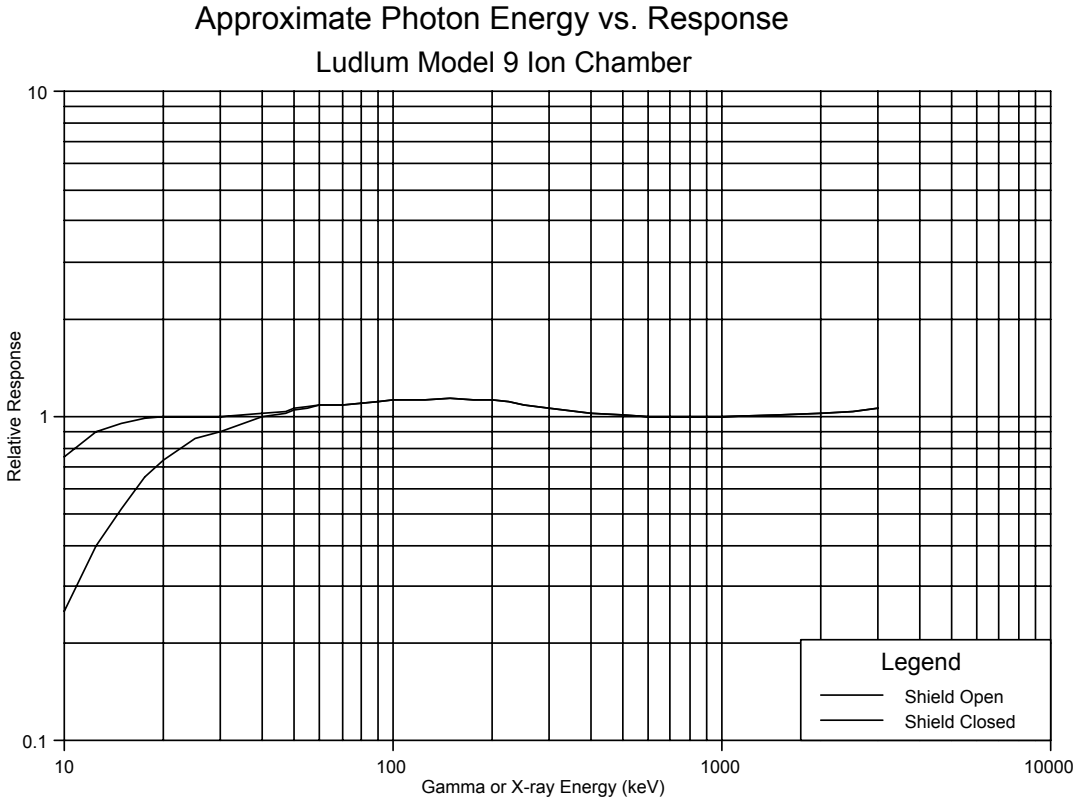
In pressurized ion chambers, the detection gas used may still be air, but it is pressurized to about six times atmospheric pressure. This technique provides a higher efficiency for the detection of photon radiation so that environmental levels of radiation can be accurately quantified. The problem is that the chamber wall must be made thicker to contain the gas at pressure, so the lower energy gammas and x rays (below about 40 keV) cannot be detected. Similarly, beta radiation cannot be detected with pressurized ion chambers since there is no way to design a thin window to contain the pressure. Thus, they can always be identified by the fact that they have no beta window.

Gamma Response

Ion chambers, when used to quantify gamma and x radiation, measure the exposure rate present in units of R/hr (or mR/hr or kR/hr). They are not particularly suited for low-level measurements, say, much below 1 mR/h. Some units are available which posses an "integrate" function, so that the instrument can be left in a location for a long period of time and an average exposure rate determined. Lower-level measurements can be obtained using this method.

The benefit and the beauty of ion chambers is that they are capable of accurately quantifying the full range of gamma energies which are of practical interest in radiation protection. Even better is the fact that, unlike G-M detectors (and scintillation detectors), response to all of these different energies is relatively even. Radiation exposure rates from a complex or unknown energy spectrum can be determined directly and easily. Figure 6 shows the energy response curve for the Ludlum Model 9 ion chamber, which is more-or-less typical of most ion chambers.

***Figure 6**. Energy Response Curve for a Ludlum Model 9 Ion Chamber*



Another benefit of ion chambers is that they are very good (a "must," in fact) for measuring very high exposure-rates. Unlike G-M detectors, there is no loss of efficiency in higher radiation fields. Also, unlike G-M detectors, ion chambers will simply "peg" off scale when exposed to a radiation field higher than the detection capability of its highest scale. G-M detectors tend to saturate and fall to zero in an extremely high radiation field.

Beta Response

Since the roentgen is defined only for gamma and x radiation, a different unit must be used in measuring the exposure from beta radiation fields. This unit is the rad (for radiation absorbed dose—this is technically an absorbed dose rate, not an exposure rate). Therefore, beta radiation fields are measured in rad/hr or mrad/hr, not R/h or mR/hr, despite what is printed on the meter face.

So, it would appear that to determine the beta component of a radiation field, you simply subtract the exposure rate measured with the beta window closed from the exposure rate measured from with the beta window open. The gamma component would be reported in mR/hr or R/hr and the beta component would be reported in mrad/hr or rad/hr. Unfortunately, a factor needs to be applied to the beta component for two reasons. First, for an ion chamber calibrated to a photon field, the response will not be identical to that from a beta field. Second, photon exposure rates are measured for the *center* of the ion chamber

volume, while beta exposure rates are measured for the *entrance window* of the ion chamber. This is so that the potential for beta dose to the skin (or lens of the eye) of a worker can be assessed. A beta correction factor (CF), in units of rad/R, must be applied to the difference between the open and closed window readings. The CF can usually be obtained from the manufacturer, but is generally on the order of 3 to 5.

$$\text{Reading with Window Closed} = \text{Photon } \frac{\text{R}}{\text{hr}} \text{ at effective center of chamber}$$

$$(\text{Window Open} - \text{Window Closed}) \times \text{CF} = \text{beta } \frac{\text{rad}}{\text{hr}}, \text{ at the entrance window}$$

Example: Using a Ludlum Model 9 ion chamber (CF = 3.7 rad/R), the measurement in contact with the floor with the window open is 65 mR/hr. In the same spot, with the window closed, the measurement is 35 mR/hr. What are the gamma and beta components?

Solution: The gamma component is that reading taken with the window closed, or 35 mR/hr at the center of the detector. The beta component is

$$\left(\frac{65\,\text{mR}}{\text{hr}} - \frac{35\,\text{mR}}{\text{hr}}\right) \text{x} \frac{3.7\,\text{mrad}}{\text{mR}} = \frac{111\,\text{mrad}}{\text{hr}} \text{ beta, at the entrance window}$$

One other note in assessing beta exposure is that ion chambers should not generally be used to assess small spots of beta contamination (i.e., *smaller* than the area of the beta window); the indicated absorbed dose rate will be less than the true absorbed dose rate.

Calibration

Ion chambers, like all radiation detectors, must be calibrated periodically. This is often yearly, but may be more frequent for some licensees. If a substantial repair is made to the instrument, such as replacing a meter movement or changing a mylar beta window, re-calibration should be performed. The calibration consists of two parts.

The first step of an ion chamber calibration is the pre-calibration. This is a check to make sure that the instrument is mechanically sound, the meter is properly "zeroed" with the power off, the beta window is not punctured, all of the batteries and the battery check indicator are functional, the desiccant is active, and that all of the functions of the detector are operational. A contamination survey of the instrument is also performed. A precision check, in which the detector is exposed several times to the same source strength, is performed to make sure that the detector responds consistently.

In the second step, the ion chamber is exposed to a known, calibrated, uniform radiation field, usually from ^{137}Cs, at intensities which will give measurements of about 20% and 80% of full scale. The ion chamber is adjusted so that each of these points is within ±10% of the known value. This two-point calibration is done on all scales.

Because ion chambers are sensitive to temperature and atmospheric pressure, it is important that an ion chamber be calibrated under conditions which will at least approximate the conditions under which it will be used. Alternately, correction factors obtained from the manufacturer should be

provided to the calibration facility to correct for their altitude and weather conditions. Atmospheric pressure, temperature, and relative humidity at the time of calibration should be recorded on the Certificate of Calibration.

Use of Ionization Chambers

Ion chambers are ideally suited to high exposure rate situations, and are really the only suitable instrument when the energy spectrum of the radiation field is composed of low-energy photons, or is composed of an unknown or complex series of photon energies. There are a few items to keep in mind.

Some ion chambers require a warm up time of about five minutes to stabilize the voltage applied to the detector. Make sure you allow the ion chamber to warm up before use if the operation manual requires it. Some other instruments get around this warm up time by using a second battery (permanently installed on the circuit board) to keep the chamber at voltage all the time. The lifetime of these batteries is usually several years or more, but often there is no indication when these batteries have failed—the "Battery Check" function usually only checks the "regular" batteries which drive the other circuitry. (This problem does not exist in ion chambers which require a warm up time because the same batteries power *all* of the components.) If you do purchase an ion chamber which doesn't require a warm up time longer than a few seconds, ensure that you get one which has a feature to test the "collection potential." Check the condition of the batteries (all of the batteries) frequently.

Once the ion chamber has been turned on (and warmed up, if applicable), the meter must be electronically "zeroed." This is done by bringing the instrument to a low radiation area, setting the instrument to its most sensitive scale, and adjusting the "zero" knob until the needle indicates zero. (This function can also be used to subtract out "background.") A source check should be performed *every time the instrument is turned on*.

Most troubles with ion chambers come from not changing (or regenerating) the desiccant frequently enough. The desiccant is usually located inside the instrument, directly attached to the detector. Air vented into and out of the ion chamber passes through the desiccant, which changes color (often from blue to pink) as it absorbs moisture. The desiccant should be checked frequently and changed on a regular basis. Desiccant can be regenerated by drying it in an oven at 150° for a couple of hours. Failing to keep dry desiccant in an ion chamber can cause it to not respond to radiation. Re-calibration is not required after changing desiccant.

The other common problem encountered with ion chambers is a punctured beta window. *An ion chamber with a punctured beta window <u>cannot</u> be considered to be operating properly.* Avoid getting punctures in the beta window by storing and transporting the instrument with the end-cap on or the window closed, and by using caution when the window is uncovered or open. Ion chambers are not used for perform-ing surface scans, so it isn't too difficult to make a window last for years. If a window is punctured and replaced, a re-calibration must be performed.

Air-vented ion chambers should not be used in the presence of radioactive gases or vapors, as these will migrate into the detector chamber. Even a small amount of a radioactive gas or

vapor in the ion chamber will cause an increase in background and invalidate your survey results. The presence of the desiccant is also no guarantee that tritium vapor will be prevented from entering the chamber.

Most ion chambers use magnetically operated switches to change ranges. Exposure to strong magnetic fields, then, can prevent proper operation. The manufacturer or operation manual will give details about what levels of magnetic field will adversely affect operation. Only one manufacturer I am aware of (Bicron) uses proprietary technology to completely avoid the need for magnetic switches or relays.

Most ion chambers do not have an audio response because the exposure rate is determined in terms of the magnitude of electrical current rather than in counts or pulses. One manufacturer (Ludlum Measurements, Inc.) provides an "imitation" audio response. In this, a regular clicking can be heard, the frequency of which is proportional to the exposure rate. This feature is often desirable.

Conclusion

Ion chambers are excellent for quantifying levels of x and/or gamma radiation of a few mR/hr or more. They are also excellent for discriminating between photon and beta particle radiation, and accurately measuring both components. They are the best instrument available for quantifying high levels of x, gamma, and beta radiation. They should not be used routinely for surface scan surveys or for personnel or equipment frisking. Gamma and x-ray surveys are reported and recorded in units of R/hr or mR/hr, while the results of beta surveys are reported and recorded in units of rad/hr or mrad/hr. Pressurized ion chambers are more sensitive to low exposure rates, but may be too large to be easily used as portable instruments, can't discriminate between beta and gamma radiation, and generally have to be left in place for many hours or days in order to make a measurement. Not every facility which uses radioactive material has need for an ion chamber.

If your facility has areas in which high exposure rates exist, where the potential for high exposure rates exist, or if you use x-ray machines, an ion chamber would be a valuable addition to your instrumentation.

The Author

Paul R. Steinmeyer is a health physicist at Radiation Safety Associates, Inc., and the co-author of *Mathematics Review for Health Physics Technicians.*

RSA Laboratories, Inc.
21 Pendleton Drive, PO Box 61
Hebron, CT 06248

860/228-0721

E-mail: prstein@radpro.com

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