RADON MONITOR

Build this radon monitor to detect a possible health threat in your home and, while doing it, learn more about radioactivity.

THIS TWO-PART ARTICLE DISCUSSES the design, construction, and use of a simple, inexpensive environmental radon gas detector that you can build. It is called the beverage can environmental radon monitor or BERM because its ionization chamber sensor is made from a readily available aluminum beverage can. You will be given a choice of methods for measuring and recording events or rates that can be translated into units of radon density.

Most people are exposed to environmental radon in excess of the natural rate because of the time they spend indoors. This first article explains what radon is, why it is a health hazard, and the importance of knowing the level of radon in the rooms of your house where you spend most of your time while indoors. It also includes the information needed to build the ionization chamber, its amplifier circuitry, and alternative circuits for charging the chamber's internal high-voltage capacitor to 500 volts.

The second part of this article covers pulse-rate measurement, instrument calibration, and the conversion of pulse rates to radon density units. The article also offers alternative methods and circuits for performing these functions.

Even if the BERM is only crudely calibrated, it can warn you of unsafe radon levels in your home. However, when properly calibrated, it can give readings that compare favorably with those obtained from professional radon monitoring instru-

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ments costing thousands of dollars. Constructing the BERM will give you "hands on" experience in measuring a common form of radioactivity, and give you a better understanding of how it produces isotopes, subjects not easily grasped in lectures or from reading.

The cost of parts to build the BERM, exclusive of a power supply, is typically less than $20. Because most of the components are readily available, you might be able to reduce even that modest cost by making use of parts you already have on hand. You will need the standard electronic technician's set of hand tools as well as such basic electronic test equipment as a two-channel oscilloscope and either an analog or digital multimeter.

What is radon?

Radon is a natural, inert, radioactive gas emitted from the earth. Odorless, colorless, and invisible, it is a byproduct of the radioactive decay of uranium. Because it is inert and does not chemically bond to elements, it is released from the soil into the atmosphere. Radon is emitted almost everywhere on earth, but some geographical regions have higher concentrations than others, depending on the local geology and soil porosity.

Radon becomes a health problem when it decays and produces other short-lived isotopes called *daughter products* or *progeny*. These chemically active isotopes are usually formed as charged particles (ions). They bond readily to other substances such as dust and smoke particulates. Table 1 lists a portion of the decay chain of radon 222 and its short-lived progeny.

When radon decays, it releases alpha particles with an energy of 5.5 million electron volts (5.5 MeV). That would seem to be a large amount, but alpha particles travel only 4 to 7 centimeters (1.5 to 2.5 inches) in air before dissipating their energy in the ionization of air molecules. A piece of paper or even human skin is thick enough to stop alpha particles. Direct exposure to radon, unlike direct exposure to beta particles, gamma rays, X-rays, or even ultraviolet light, poses little risk for humans.

The health threat from radon is indirect. Energetic alpha particles can cause chromosomal damage to the thin layers of lung tissue when humans breath air contaminated by radon and its progeny. That damage is a potential cause of lung cancer, especially when coupled with the effects of cigarette smoke in the lungs.

There are several different forms of radon, but radon 222 is the most prevalent form, and is of the most concern to health researcher. The number 222 refers to its isotope number. The alpha particles emitted by radon and its progeny are helium nuclei.

Most of the radon 222 that is inhaled is either exhaled directly or it diffuses into the bloodstream where its alpha emission does little detectable damage. However, radon's short-lived progeny such as polonium 214 and polonium 218 are more likely to emit alpha particles that are capable of damaging sensitive human tissue.

The alpha particles from the decay process of polonium 218 have 6.0 MeV of energy while those from poloniun have 7.7 MeV, both higher than the 5.5 MeV of radon 222. For this reason, researchers believe that they are the agents primarily resiponible for inducing lung cancer in situations where radon 222 is present in amounts considered to be above the safe level.

Radon has been a constituent of the air for millions of years. We became aware of its existence only when instruments were developed that could detect and measure it. Its presence is of concern because of the alarming statistics on death due to lung cancer. Its presence has long been considered a contributing factor to those deaths. However, it is difficult to separate cancer attributable to radon alone from that attributable only to smoking or to smoking in the presence of radon.

The harmless concentration of radon in the outdoor air is about one-thousandth of its concentration in the ground. This can be demonstrated by placing an inverted bucket on bare ground over a suitable radon monitor. The radon emanating from the soil collects inside the bucket until an equilibrium condition is reached. The monitor will probably indicate a radon concentration that is several orders of magnitude higher than that in the surrounding air, but less than the soil concentration in the soil.

A house with a foundation, walls, floors, and a roof can be

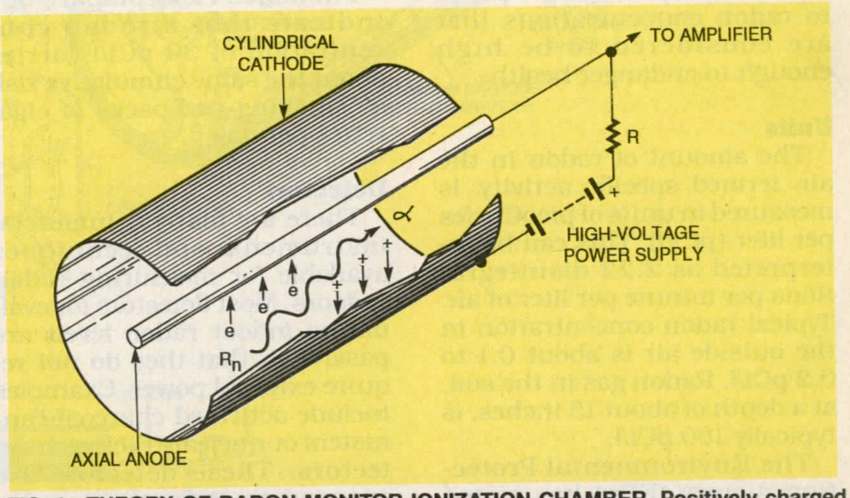

FIG. 1—THEORY OF RADON MONITOR IONIZATION CHAMBER. Positively charged anode wire attracts electrons and negatively charged cathode attracts positively charged ions. The recombination of electrons and ions causes a current that produces a voltage pulse.

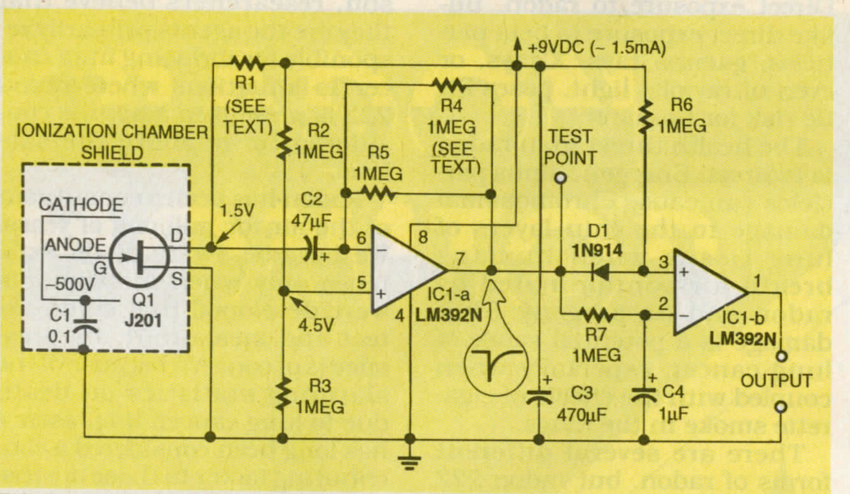

FIG. 2—RADON MONITOR AMPLIFIER amplifies voltage pulses across resistor R1 and then detects them for counting by separate pulse-rate counting circuitry.

TABLE 1
THE DECAY CHAIN OF RADON 222

Isotope	Name	Half life	Decay process	Energy
Rn 222	Radon	3.82 day	alpha	5.49 MeV
Po 218	Polonium	3.05 min	alpha	6.0 MeV
Pb 214	Lead	26.8 min	beta	1.0 MeV
Bi 214	Bismuth	19.7 min	beta	3.3 MeV
Po 214	Polonium	164 µs	alpha	7.7 MeV

considered analogous to a bucket. It will also trap radon that leaks into the indoor airspace, especially if all the doors and windows of the house are closed. Under these conditions, the indoor radon might be 10 to 100 times more concentrated than outdoor radon. People in developed countries typically spend most of their time indoors at work, at school, or at home, so they could be exposed to radon concentrations that are considered to be high enough to endanger health.

Units

The amount of radon in the air, termed specific activity, is measured in units of picoCuries per liter (pCi/l). This can be interpreted as 2.22 disintegrations per minute per liter of air. Typical radon concentration in the outside air is about 0.1 to 0.2 pCi/l. Radon gas in the soil, at a depth of about 15 inches, is typically 100 pCi/l.

The Environmental Protection Agency (EPA) has stated that a radon level within a home of 4 pCi/l or less will present little or no health threat. It has published recommendations for specific actions to be taken where higher concentration levels are found. These include follow-up testing in other rooms in the home. Nevertheless, it is ultimately up to the homeowner to decide what radon level is acceptable for his home in the absence of a scientifically established absolute safe threshold level for radon exposure.

Published risk comparisons indicate that a radon concentration of 30 pCi/l carries about the same cumulative risk as smoking two packs of cigarettes per day.

Detectors

There are many commercial instruments and techniques available for measuring radon indoors. Most detectors for evaluating indoor radon levels are passive in that they do not require external power. Examples include activated charcoal canisters or nuclear-track etch detectors. These detectors are exposed to indoor air under specified test conditions. After exposure, they are sent off to a laboratory for analysis, the same approach used in detecting X-ray exposure with passive detection badges.

The principal drawback to passive detectors is that they measure radon concentration at only one specific location for a specified period of time. Many variables influence radon concentration levels; therefore, a single estimate of radon concentration is likely to have a significant error.

Obviously, radon concentration surveys based on two or more passive measurements will provide a more accurate assessment than a single measurement, but they are expensive because the price of a "one-time-only" passive detector can range from $25 to $100. If you conduct only one test, the EPA recommends that it be run under *worst-case conditions.*

By worst case conditions, the EPA means that the test should be made in any living space in the home or building that is closest to the ground (just above the floor slab, crawl space or basement) at a time of the year when ventilation is at a minimum—typically during the winter.

The air exchange rate and type of heating and cooling system in a house or building can cause wide variations in the amount of radon present due to differences in the way air is introduced, circulated and exhausted. There can also be daily variations in radon concentration. Because randon readings might exceed limits considered to be safe, it is recommended that radon concentration levels be measured over a one-year period in different locations in the home to obtain the best estimate of long-term risk.

Only an active radon monitor such as the BERM is capable of monitoring radon continuously. Commercial instruments capable of doing that typically cost several thousand dollars. The BERM radon monitor has many of the features of the expensive instruments at a far lower price.

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compared against those of a properly calibrated test instrument. Nevertheless, even if it is not calibrated, the BERM will yield relative data that is accurate enough to indicate if a radon hazard exists in your home. You can use a BERM to locate the "worst case" room in your house where a follow-up test with a precisely calibrated monitor should be performed if you suspect excessive levels.

Ionization chamber theory

The easiest way to measure the presence of radon is to detect the high-energy alpha particles that it emits as a result of radioactive decay. As can be seen in Table 1, the alpha particle has a kinetic energy of about 5.49 MeV which ionizes the air passing through it. On average, about 34 eV is required to ionize air.

Therefore, assuming that an alpha particle dissipates all of its energy ionizing air, about 100,000 (10^5) electron-ion pairs are generated over a path length of about 4 centimeters (1.5 inches). As a result, a charge of 10^{-14} coulombs can be collected by the electric field inside the ionization chamber.

The BERM ionization chamber, shown schematically in Fig. 1, has a cylindrical form factor because it is constructed from an aluminum beverage can. It has an axial, positively charged wire anode that extends the length of the can.

Negatively charged electrons (e) are attracted to the positively charged anode and arrive a few microseconds after an ionizing event while positively charged ions (+) are attracted to the negative cathode cylinder liner. A few milliseconds later the ions recombine with electrons from the high-voltage, DC-power supply.

The resulting current flow produces a small voltage pulse across the resistor in series with the power supply. That pulse is then amplified, detected, and counted. The number of counts per minute can then be multiplied by a constant that includes the effective volume of the chamber to determine specific radon activity in units of pCi/l. The presence of radon "daughters" produced in the chamber increases the count rate.

The BERM ionization chamber design is based on the assumption that the air inside the chamber is a representative sample of the air in the room that is being monitored. The air in the BERM is slowly exchanged by diffusion through openings in the chamber.

Chamber size

A 12-ounce aluminum beverage can was selected for making the ionization chamber

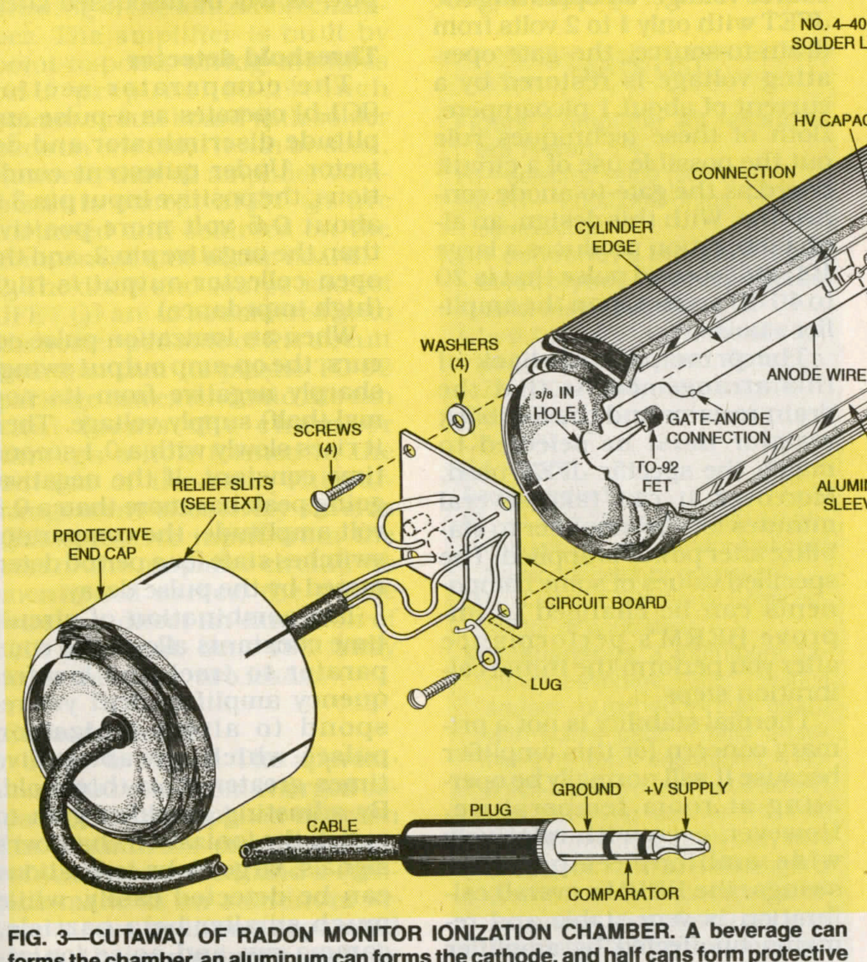

FIG. 3—CUTAWAY OF RADON MONITOR IONIZATION CHAMBER. A beverage can forms the chamber, an aluminum can forms the cathode, and half cans form protective end covers. Amplifier circuit board is shown left of center.

because, in addition to its ready availability, its size is standardized. This size uniformity permits BERM calibration based on chamber size. The can's dimensions are large enough for alpha particles to dissipate most of their energy ionizing air. As stated earlier, the amount of charge generated determines the amplitude of the current pulse collected on the anode.

Ionization caused by beta particles and other naturally occurring radiation, primarily gamma rays, causes lower amplitude pulses in a chamber of this size. This means that it is easier to discriminate the larger alpha ionization pulses from those caused by beta particles and gamma rays as well as by amplifier noise.

High-voltage supply

A nominal but stable 500-volt differential is required to set up an electric field between the anode and cathode. The ion collection efficiency of this chamber remains fairly constant over a voltage range of 200 to more than 1000 volts.

Unfortunately, any noise generated by the 500-volt supply would be coupled directly into the amplifier input. This establishes the additional requirement that the combined noise, ripple, and short-term drift be less than 100 microvolts.

The high voltage is obtained from a charged, 0.1-microfarad metallized-polypropylene-film capacitor. A suitable capacitor will hold its charge long enough to power the ionization chamber for several weeks. It must be recharged whenever the 9-volt battery is replaced.

Before using the BERM, its high-voltage capacitor must be charged from a suitable source. (Alternative methods for obtaining the required voltage will be explained later.) The high-voltage supply was designed to be stable and not be an electrical noise source.

Circuit description

Figure 2 is the schematic for the amplifier. To maximize the amplifier input signal, its capacitance must be minimized. This is done by connecting the chamber's anode wire directly to the gate of JFET Q1. The effects of excess capacitance and leakage current that would be present if a printed circuit had been used for the connection are eliminated. This approach holds total input capacitance to around 7 picofarads. An input pulse charges the gate of Q1 about 1 millivolt.

The charge must be kept on the gate long enough for the amplifier to respond. An input resistance large enough to maintain a long pulse width would introduce too much thermal noise for a good signal-to-noise ratio.

This problem was avoided by letting the gate float or self-bias. The result is that input impedance is maximized and noise is minimized.

A JFET can be self-biased because its gate leakage pulls the gate towards the drain-to-source voltage. By operating the JFET with only 1 to 2 volts from drain-to-source, the gate operating voltage is restored by a current of about 1 picoampere. Both of these techniques rule out the possible use of a circuit board as the gate-to-anode connection. With this design, an alpha ionization produces a large 100-millisecond pulse that is 20 to 40 dB greater than the amplifier's noise.

The principal drawback of this arrangement is that the drain resistor and the feedback resistor must be selected to match the specific JFET used. Moreover, it can take several minutes for the amplifier to stabilize after power is applied. The specified values of some components can be changed to improve BERM's performance after you perform the initial calibration steps.

Thermal stability is not a primary concern for this amplifier because it will normally be operating at room temperature. However, even with relatively wide ambient temperature swings, the BERM's overall calibration is very stable and remains unaffected by amplifier gain changes.

Operational amplifier

The LM392N is a low-power operational amplifier/voltage comparator performs as both an amplifier and comparator. The high-gain, internally frequency compensated op-amp is IC1-*a*, and the comparator is IC1-*b*. Both can operate from a single power supply over a wide range of voltages (3 to 32 volts). Current drain is 600 microamperes—essentially independent of supply voltage. The LM392N shown on Fig. 2 is in an 8-pin DIP package, but the LM392H in a metal can package can be substituted.

The op-amp functions as a current-to-voltage converter following the JFET's transconductance stage. Overall voltage gain is about 60 dB. However, amplifier power gain, due to the impedance transformation, is about 160 dB! To prevent regenerative feedback, the JFET's input must be electrically shielded from the op-amp's output, as will be discussed later.

Threshold detector

The comparator section (IC1-*b*) operates as a pulse-amplitude discriminator and detector. Under quiescent conditions, the positive input pin 3 is about 0.5 volt more positive than the negative pin 2, and the open collector output is high (high impedance).

When an ionization pulse occurs, the op-amp output swings sharply negative from its normal (half) supply voltage. Then it rises slowly with a 0.1 second time constant. If the negative-going peak has more than a 0.5 volt amplitude, the comparator switches state for a period determined by the pulse decay.

The combination of circuit time constants allows the comparator to track the low-frequency amplifier drift yet respond to alpha ionization pulses which are about five times greater than threshold. By adjusting amplifier gain to match the ionization chamber's signals, large alpha ionizations can be detected easily, while much smaller beta particle, gamma ray, and noise ionizations are rejected.

The comparator's output is an open collector which goes low (low impedance) whenever an alpha particle is detected. This output can be interfaced to any logic device, digital counter, or count-rate meter. This will be discussed in detail in Part 2 of this article.

Low-voltage power supply

The optimum low-voltage power supply for the amplifier is a 9-volt, battery. The BERM draws only a few milliamperes, so a 9-volt alkaline transistor battery is should provide an effective life in excess of 50 hours—in addition to permitting it to be a portable instrument. However, if you would prefer to power your BERM from the AC line, a schematic for a suitably filtered 120-volt AC to 9-volt DC converter will be in Part 2 of this article.

Chamber arrangement

Refer to Fig. 3, a cutaway drawing of the ionization chamber. The amplifier is built by point-to-point wiring methods on a prepunched 1¾-inch square circuit board with solder pads on one side. It can be seen, however, that all amplifier components except JFET Q1 are mounted and soldered on the component side of the board.

The drain and source leads of JFET Q1 are to be soldered onto the solder-pad side of the circuit board so that its plastic TO-92 package can extend into the can that forms the chamber through a hole formed in the bottom of the can. This arrangement effectively shields Q1's sensitive input from the rest of the amplifier circuit. As mentioned earlier, the anode wire is a direct an extension of Q1's gate lead, bent 180° away from the other two leads.

Cathode sleeve

Refer to Fig. 3. The approximate 500 volts from charged capacitor C1 are applied between the aluminum can chamber, which is grounded, and a cathode made as an aluminum inner sleeve or lining separated from the can's inner wall by sheet plastic insulation. This

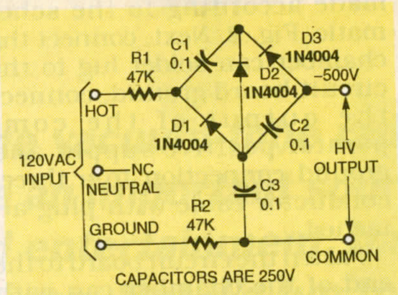

FIG. 4—VOLTAGE TRIPLER CHARGES ionization chamber capacitor. It is powered from the 120-volt AC line.

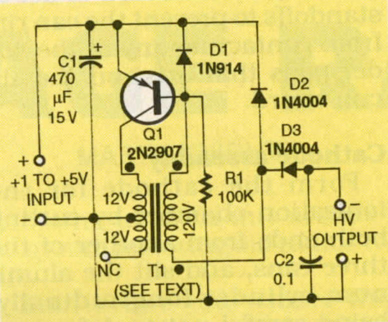

FIG. 5—BLOCKING-OSCILLATOR flyback circuit powered from DC is an alternative for charging the ionization chamber capacitor.

PARTS LIST

Figure 2 amplifier All resistors are ¼-watt, 5%.

R1—selected value (see text)

R2–R7—1,000,000 ohms, carbon composition

All capacitors are aluminum electrolytic, 15-volts, unless otherwise specified

C1—0.1 µF, 630 volts, metallized-polypropylene film, Sprague 730P104X9630 or equivalent

C2—47 µF

C3—470 µF

C4—1 µF

Semiconductors

IC1—LM392N operational amplifier/voltage comparator,National Semiconductor or equivalent

Q1—J201 JFET, National Semiconductor or equivalent

Miscellaneous 3 aluminum 12-ounce beverage cans, 1¾-inch square, punched circuit board with solder pads (Radio Shack No. 276-159 or equivalent), 4 No. 4 self-tapping sheet metal screws and matching washers, 1 4-40 screw and nut, polyethylene sheet (see text), 30-inch length of 3 conductor cable, ¼-inch diameter phone plug, 9-volt alkaline transistor battery, solder lugs, electrical tape, solder.

sleeve-within-a can construction provides the unit with excellent shielding from electrical noise.

With this design, the effective volume of the ionization chamber is considerably reduced, compared to its physical volume, because the electric field includes the end surfaces of the can. These end-surface fields must be accounted for during instrument calibration.

Chamber assembly

Obtain three identical clean, undented, 12-ounce aluminum beverage cans. (They are 4.8 inches high.) Cut the top from the tab end of one can to form the ionization chamber with a can opener so that a crimped-on ring remains. Form a ⅜-inch hole in the center concave bottom of the can.

Then, using the blank 1¾-inch square circuit board specified as a template, drill four small pilot holes on the rim at bottom of the closed end of the can, on top of its circular ridge. Later in the assembly procedure, self-tapping machine screws will be used to mount the circuit board on the end of the can as shown in Fig. 3.

Hold the circuit board in position on the end of the can with the solder tabs directed toward the can. Look in the open end of the can through the ⅜-inch hole and mark the locations of the solder pads that are suitable for Q1's drain and source pins. Plan your parts layout carefully so that one of those pads can be common to the ground or negative power supply pin on op-amp IC1-*a*.

Circuit assembly

Refer to Fig. 2. The selection of the value for drain resistor R1 will depend on the characteristics of the specific J201 JET (Q1) to be used in the circuit. Short the JFET's gate to its source and measure the drain-to- source current (I_{DS}) with a drain-to-source voltage of about 1.5 volts. Then calculate the drain resistor value based on this current and the voltage of the power source you intend to use:

Drain resistor R1 = $(V_S - 1.5)/I_{DS}$
For a J201 FET and a 9-volt battery, R1 should have a value between 10 and 33 kilohms.

When constructing the amplifier, use 1-megohm resistors for both parallel resistors R4 and R5. Form the axial leads of both resistors and solder them so that R5 will remain permanently in position while provision is made for the easy removal of R4 during the calibration process. By doing this, gain can be adjusted later by shunting 1-megohm resistor R5 with another value for resistor R4 until an optimum value is found.

Solder a short tinned wire to the output pin 7 of op-amp IC1-*a* to act as a test point to permit attaching an alligator clip lead or oscilloscope probe. Place a solder lug under one of the sheet metal screws holding the circuit board in position on the end of the can to act as a convenient circuit common or ground lug.

Other than this restriction on the placement of Q1 on the circuit board, the layout of the other components is not critical. Use the convenient pad locations bridged by the components you've selected and any necessary jumper wires to complete the wiring of the circuit. Complete the insertion and soldering of all components on the circuit board except for JFET Q1.

Insert and solder the source and drain leads of JFET Q1 on the solder-pad side of the board. Then carefully bend the gate lead directly away from the other two leads so that it is perpendicular to the solder-pad side of the circuit board.

Solder a length of bare copper wire (28 to 32 AWG) about 4 inches long to the gate lead of Q1, and straighten it so that it is perpendicular to the circuit board. Cut the free end of the anode wire to a length that is about 4½inches long. Twist a small loop (about 1⁄16-inch in diameter) on the end of the anode wire and solder the joint.

Carefully examine the circuit assembly to be sure that it was made according to the schematic, Fig. 2. Next, connect the chamber can solder lug to the circuit-board ground, connect the output of the comparator,positive supply, and ground connection to a three-conductor cable with plug attached.

Fasten the circuit board to the end of the chamber can with four No. 4 self-tapping sheet metal screws. Use small matching washers between the can rim and circuit board to act as standoffs to prevent the can rim from contacting any of the solder pads that exist on the circuit board.

Cathode assembly

Form the cathode for the ionization chamber by cutting both ends from another of the three cans, and slit the aluminum cylinder longitudinally, being careful not to deform or flatten it. Trim, square the ends of this aluminum sleeve to a length of about 3.7 inches. File off any sharp edges or burrs that could cut through the thin plastic insulation layer to be applied later.

The aluminum in the can has intrinsic spring qualities, so that if its slit edges are overlapped about ¼-inch they will retain their tendency to spring open. Cut two slots about ¼-inch deep and about ⅛-inch apart at right angles to the slit edge of the aluminum cylinder. Those slots form a "digit" for later termination of one end of capacitor C1.

Wrap and crimp a short length of tinned lead wire around this digit as shown in Fig. 3 so that when the cathode sleeve is installed in the can, the lead can be soldered to one end of C1.

The inner wall and ends of these cans have a plastic coating, but it is not dependable as an insulator between the cathode sleeve and the chamber can. Cut a sheet of polyethylene plastic approximately 2 mils thick sheet so that it will extend about ¼-inch beyond each end of the cathode sleeve and overlap its circumference. This material can be taken from sandwich bags, cleaner's garment bags, or other sources.

Drill a small hole in the rim of the can and fasten a small solder lug inside with a No. 4-40 machine screw and a nut as shown in Fig. 3. After being sure that all the metal chips and filings have been cleaned from the chamber can, insert the insulating film and press it against the inner wall of the can and then insert the cathode sleeve. After the insulated cathode has been inserted, check to be sure that there is no metal-to-metal contact between the can and sleeve.

Capacitor installation

Carefully select high-voltage capacitor C1 to make sure that it is a high-quality, low leakage component. If left fully charged, it should retain at least 37% of its charge for at least a month at room temperature.

Solder capacitor C1 to the internal lug with as short a length of lead as possible, as shown in Fig. 3. Position the capacitor in the mouth of the can against the side wall as shown in Fig. 3. Then solder the short wire stub on the cathode to the free end of capacitor C1. Clip its lead short and bend it toward the center of the can so that an alligator clip can be attached to it. Finally, check the resistance between the cathode sleeve and chamber can to be sure that it is effectively infinite.

Protective covers

Cut a third can in half and bend the tab of the top end back to its original unopened position. Carefully slip this top can half over the open end of the chamber can. Expect that it will form a tight "press fit." If the fit is too tight for easy removal, cut several longitudinal slits in the can half to permit slight expansion (see Fig. 3).

Drill a hole in the bottom of the other half can large enough to be able to insert a small rubber grommet which will pass the three-conductor cable. This can end will cover the circuit board and shield it from 60-Hz noise.

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Initial checkout

Apply power to the ionization chamber with the cable and connect an oscilloscope to the op-amp test point shown in Fig. 2. After several minutes, JFET Q1 should have stabilized at its normal operating point with the drain at about 1.5 volts. The output of op-amp IC1-*a* should be half the 9-volt supply voltage with about 50 to 200 millivolts of low frequency noise riding on top of it.

When the amplifier is working properly, try to avoid bumping or vibrating the chamber because it is a sensitive vibration sensor, made even more sensitive as long as the anode wire remains unsupported. Shocks or vibrations will show up as large-amplitude, slow decaying sinewaves.

If the amplifier oscillates, produces square waves, or will not settle down after several minutes, check the drain voltage of JFET Q1 and the quality of the coupling capacitor C2. The amplifier circuit might have too much gain which can be reduced by substituting smaller values for resistor R4. Start with a 333 kilohm resistor which will reduce gain about 50%.

Anode support

Punch two small holes on the opposite sides of the can's rim as shown in Fig. 3. Insert a length of nylon monofilament fishing line through one hole, pass the free end through the loop at the end of the anode before passing it through the second hole. Pull both free ends of the line together around the outside rim of the can and, keeping tension in the line, tie them together with a knot. If the tension on the line is sufficient, the end of the anode will remain centered in the mouth of the can.

If a persistent 60-Hz waveform appears at the test point, pass a length of insulated hookup wire through the cable grommet in the bottom of the end cap and hook it up to repeat the test. Press on the end cap and examine the waveform again. If this shielding doesn't cure the problem, check carefully for other construction errors such as a missing ground connection or a noisy power supply.

Gain adjustment

Assuming that the ionization chamber and amplifier comply with the initial checkout requirements, it should be ready to detect alpha particles. However, additional amplifier gain adjustments might be necessary. Charge the capacitor C1 to −500 volts, and put the end cap back on. If you have no means for charging the capacitor, this can be done with either the voltage-tripler circuit shown in Fig. 4 or the DC converter shown in Fig. 5.

The voltage tripler shown in schematic Fig. 4 operates directly from the 120-volt AC line. It will produce a voltage close enough to 500 volts for satisfactory operation of the BERM. Because of the shock hazard associated with line-powered circuits, the use of a grounded, three-wire plug and line core is strongly recommended. This circuit should be enclosed in a suitable protective case to prevent accidental contact with the power line and any of the three large electrolytic capacitors C1, C2, and C3.

The DC converter schematic shown in Fig. 5 is a blocking-oscillator flyback circuit which can be powered from an adjustable, low-voltage DC supply. It will produce an output of several hundred volts with an input as small as 1 volt. Measure the converter's output with any voltmeter capable of measuring 100 volts before connecting the output to capacitor C1. Transformer T1, used as a step-up transformer in Fig. 5, can be any stock 20 VA transformer with a 120-volt primary and a 12-volt secondary.

Apply power to the amplifier and wait for its activity to settle. Typically, it will take several minutes for JFET Q1's gate to charge up and probably will take another minute for the coupling capacitor to charge before amplifier output reaches half supply voltage.

With the oscilloscope set for 1 volt per division and very slow sweep (0.2 second per division), the test point voltage should vary slightly as you wait to see an event. Expect the appearance of a large negative pulse (see the waveform in Fig. 2) on the oscilloscope screen indicating that you have just been lucky enough to capture your first alpha particle.

In a typical home you will see a few of these pulses each minute. However, because you are observing a random radioactive process, you might see several pulses or none in any given minute. Watch the oscilloscope screen for a few minutes and estimate the pulse amplitudes.

If the BERM amplifier has too much gain, the amplifier's output will saturate. However, if most of the pulses have an amplitude less than ½-volt, gain must be increased. The optimum gain setting occurs when pulses with peak amplitudes of about 2- to 3-volts appear without saturating the amplifier. Adjust the values of feedback resistors R4 and R5 to accomplish this.

Comparator

The last step in the check-out procedure, after gain adjustment has been completed, is to verify comparator operation. With an external pull-up resistor (100 kilohm to 1 megohm) connected to the positive supply, check its output with the second channel of your oscilloscope.

You should be able to verify that pulses with amplitudes over ½ volt drive the output low. Then complete the assembly of the BERM by putting the circuit board end cap back on.

Pulse counting and calibration

The second part of this article covers alternative pulse-rate counting techniques, calibration, sources of error and the conversion of pulse counts to specific activity to determine estimated amounts of radon present in the air. Ω

RADON MONITOR

Build this radon monitor to detect a possible health threat in your home and, while doing it, learn more about radioactivity.

PAUL NEHER

THIS IS THE SECOND PART OF A TWO-part article on the design, construction and use of a simple, inexpensive environmental radon gas monitor that you can build. It is called the beverage can environmental radon monitor or BERM because the ionization chamber sensor is made from a readily available aluminum beverage can. The first part of this article explained radon and described the construction of BERM's ionization chamber and amplifier circuitry.

As was explained in the first part of this article, most people are exposed to environmental radon in excess of the natural rate because of the time they spend indoors. The article explained what radon is, why it is a health hazard, and the importance of knowing the level of radon in the rooms of your house where you spend most of your time while indoors. It also included the information needed to build the ionization chamber and its amplifier circuitry, and alternative circuits for charging an internal high-voltage capacitor to 500 volts.

The second part of this article covers such subjects as calibration and the measurement of events or rates. It offers alternative methods and circuitry for performing these functions.

Counting techniques

To determine picoCuries per liter of activity, it is necessary to count the number of pulses over a period of time, say an hour, and determine the average count per minute. It will be necessary to divide this count by the effective volume of the chamber and factor in the effect of radon daughters, which also produce alpha ionizations, to come up with an estimate of the radon concentration.

Because this count is a random process, any estimate is meaningful only when accompanied with some indication of probable error. This indication of error includes the statistical uncertainty of the count as well as uncertainty in the volume of the chamber and other factors. Later in this article, formulas will be given for the conversion

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Rate meter

A count-rate meter will meet your requirements for counting and averaging. The circuit schematic for a count-rate meter is shown in Fig. 6. The components on the left side of the schematic function as the basic pulse-rate count circuit, while those on the right side condition the output of the analog voltmeter M1.

When the amplifier comparator IC1 (IC1-b) pulls the input to ground, capacitor C5 in the rate meter discharges through emitter-base diode D2 (Q2). Then, when the comparator goes high, resistor R8 charges C5 through emitter-base diode D3 (Q3) and accumulation capacitor C6. These components form a simple "charge pump" which charges accumulation capacitor C6 at a rate determined by the pulse rate.

The current flowing out of C6 through R9 is proportional to the accumulated charge and, at equilibrium, equals the current flowing in. In other words, the pulse rate determines voltage V_R across 100-megohm resistor R9. The equation for this response is :

$V_S = r \times R9 \times C5 \times (V_S - 2V_D)/(1 + r \times R9 \times C5)$

Where r = the pulse rate in counts per second, V_S = the supply voltage, and V_D = the diode forward voltage drop (0.5 volt).

This function is approximately linear as long as the product $r \times R9 \times C5$ is small compared to unity. If, for example, the circuit is designed so that the maximum count rate develops a voltage across R9 that approaches 10 % of the supply voltage, the maximum nonlinearity error will be 2 %.

With a regulated 9-volt supply, this circuit develops about 120 millivolts (V_R) with an input rate of 20 counts per minute where (r = 20/60 counts per second).

The value of accumulation capacitor C6 doesn't enter into the previous equation. Time constant (C6 × R9) must be sufficiently long with respect to the pulse interval to produce a reasonable average. The uncertainty of the count rate, as a function of this time constant, is given by:

$U_r = \sqrt{(r/2RC)}$

This circuit has an RC time constant of 1000 seconds. This means that it will take about an hour to settle to within 3% of its final value. It has a half-scale uncertainty (10 counts per minute) of ± 5 %.

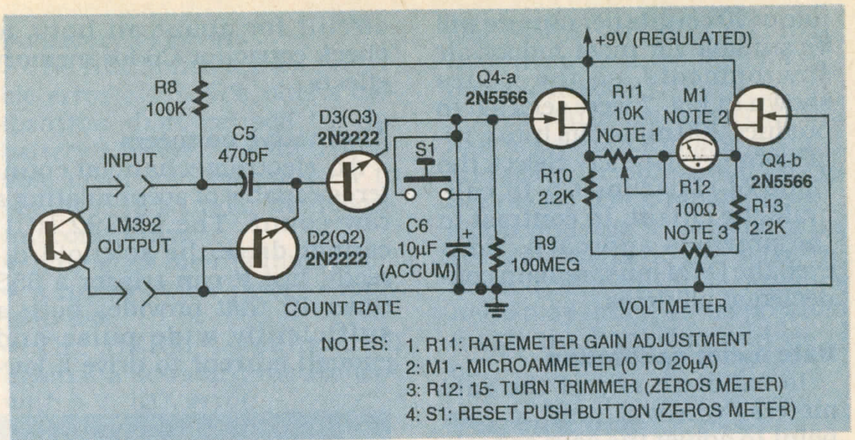

FIG. 6—THIS PULSE-COUNT RATE circuit for the BERM is coupled by to the ionization chamber with a three-wide cable.

Voltmeter

The right half of the Fig. 6 schematic is an analog panel voltmeter with a very high input resistance so that it does not load the rate circuit. Figure 6 shows a 20-microampere meter, but if you want to save money, the lower cost 50-microampere meter will work as well.

Alternatively, if you do not want a permanent system, you can substitute a bench volt-ohm milliammeter (VOM) in place of resistor R11 and the microammeter, and modify the circuit accordingly to match your meter's lowest scale. With this approach, the meter need only be connected when you want a reading.

Meter zero-adjustment resistor R12 can compensate for ± 6 millivolts of differential offset voltage in dual FET Q2. With that compensation in addition to the mechanical adjustment on the meter movement, you should be able to zero the meter with accumulation capacitor C6 discharged. If this does not happen, recheck the circuitry for possible errors.

Component selection

The leakage of diodes D2 and D3 of Fig. 6 (formed with the emitters and bases of 2N2222 transistors) as well as capacitor C6 must be low if this rate meter circuit is to work properly. The emitter-to-base junctions of a 2N2222 transistor has three orders of magnitude lower reverse current than a 1N914 switching diode.

Test electrolytic capacitor C6 for leakage before using it in the circuit. Select one that has an internal leakage resistance that is at least ten times greater than resistor R9. An effective capacitor will have a self-discharge time constant greater than three hours. Most capacitors tested by the author held at least 1 volt for 24 hours.

Don't forget the memory effect of electrolytic capacitors, especially if they have been recently operated at a voltage higher voltage than a few hundred millivolts. Some electrolytic capacitors recharge themselves to a small fraction of their operating voltage after being temporarily discharged.

Another alternative

You can also use a digital voltmeter with a constant 10-megohm input resistance and the pulse-rate circuit shown in Fig. 7. The five components of the rate circuit in Fig. 7 will fit on the amplifier circuit board with careful layout.

Typically, a full-scale count

rate of 20 counts per minute will be suitable for most indoor air environments, so the values shown in Fig. 7 were selected to produce 200 millivolts into a 10-megohm resistance. Select the value of capacitor C5 to calibrate the circuit. In contrast to the previous approach, however, the DVM must remain connected at all times.

Rate meter calibration

To calibrate any of the rate meters, you will need a data point to adjust the gain or scale factor. You can build a pulse circuit based on the 555 silicon monolithic timer IC (e.g., NE555N or MC1455N) as shown in Fig. 8. It produces about 10 pulses per minute to establish the slope of the rate meter's response when input counts per minute are plotted against the rate meter output scale.

Calibrate the pulser's rate by counting oscillations for 10 minutes so it will be within 1% accurate. Connect this auxiliary pulse circuit to the rate meter and let it settle for at least an hour before adjusting gain potentiometer R11. It might be necessary to substitute an alternative value for capacitor C5, depending on which version of the rate meter you build. You should be able to calibrate the meter to within a few percent in this way.

Combine the two

The rate meter shown in Fig. 6 and the amplifier together draw a supply current of about 3 milliamperes. They will both work from a standard 9-volt transistor battery. If you want a portable radon monitor, you can put both circuits together in a common enclosure.

Reset pushbutton switch S1 across capacitor C6 will be useful if you should accidentally bump the ionization chamber against a solid object. The large number of false readings will overload the meter which will take a long time to settle unless switch S1 is pressed.

Periodically check the rate meter zero setting by resetting capacitor C6. Do not apply any input pulses to the rate meter circuit for about an hour to check capacitor C6 for memory effects.

Alternative counters

An electromechancial counter is capable of accumulating a raw count. The LM392 (IC1) cannot drive the solenoid directly, but it can trigger a 555 timer IC that provides both a sufficiently wide pulse and enough current to drive a low-voltage counter.

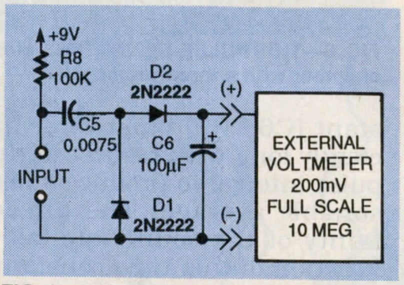

FIG. 7—AN ALTERNATIVE CIRCUIT for pulse-count determination if an an external voltmeter is be used in place of the meter.

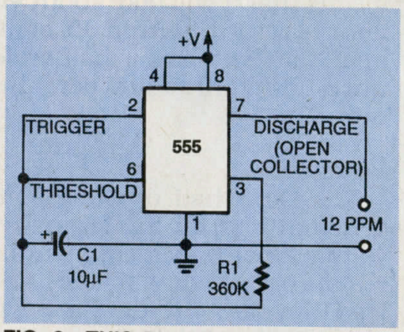

FIG. 8—THIS PULSE COUNT reference circuit can be used to calibrate the pulse-count rate circuit.

Some benchtop frequency counters include a scaler setting that will allow you to make a direct connection to the ionization chamber so you can accumulate counts. Alternatively, you can build a digital counter with an LSI counter/display driver IC.

Computer interface

If you are a computer enthusiast you might want to use your PC to count the pulses, compute a running-time average, and display the results graphically. The interface to your computer probably makes use of a latched interrupt request. A separate RS flip-flop board, set by the active-low, open-collector output, can provide the latch that is reset by the interrupt handling routine. The count rate will typically be less than 10 counts per minute, so processing speed is not critical.

An advantage of the open-collector output from the ionization chamber is that it can be pulled up by the computer logic supply (5-volts, 10 kilohms) without the requirement that the noise-sensitive amplifier circuitry share a common (electrically noisy) positive supply voltage. The chamber ground should be connected to the computer ground.

The largest calibration error relates to the proper determination of the ionization chamber's effective volume. Compared with that uncertainty, most of the other contributing sources of error in the BERM are small—approximately 10%.

Gain equation

The specific activity of radon, a(Rn), as a function of system variables is given by the following equation:

$a(Rn) = r \times k/(n \times VE)$

where a(Rn) is in units of picoCuries per liter

r = the count rate in counts per minute

k = a conversion factor from disintegrations per minute to picoCuries

n = the number of alpha counts per radon atom

VE = the effective volume in liters = physical volume × efficiency.

The constants $k/(n \times VE)$ equal 1.9 for a chamber equipped with a radon progeny filter. At 5 counts per minute, the radon concentration is 9.5 pCi/l.

If the construction instructions given in part 1 of this article were followed, the result should be a BERM that will have the same calibration factor as the author's prototype. The basic accuracy of your instrument will be ± 25%, which accounts for the probable mechanical variations, the statistical uncertainty in the author's calibration, and any rate meter error.

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Radon progeny error

Refer to Fig. 9. The conversion factor n, number of alpha emissions per radon atom, has a theoretical value of 3 because, for every radon disintegration, two more alpha particles are emitted from polonium 218 and polonium 214 (See Table 1) under equilibrium conditions.

As radon decays, the number of progeny atoms increases until their radioactive decay balances their rate of production. After radon is introduced into the chamber, the alpha production rate will stabilize in about two hours.

If the ionization chamber is open to the air so that radon and radon progeny can enter the chamber freely, there is a reading uncertainty caused by their unknown equilibrium state. Researchers have found wide variations in the ratio of short-lived daughter products compared to radon in indoor air.

This factor has been estimated to average 20 ± 14 %. A simple progeny filter made from a plastic or paper bag eliminates this source of error. However, even with a filter in place, radon diffuses slowly through the paper or plastic, and it might take up to eight hours for the reading to stabilize. The installation of a simple BERM filter is described later.

Rate meter error

Because rate meter gain is directly proportional to the power supply voltage, you should know that the calibration shifts with decreasing battery voltage. The voltage of a typical 9-volt battery will fall approximately 20% over its useful lifetime. This has been found to permit about three days of continuous operation.

The rate meter, with a time constant (RC) of 1000 seconds, has an uncertainty that depends on the rate r, assuming the background rate is negligible, and as stated earlier, has a ± half-scale error. If the count is accumulated by other means, the statistical uncertainty in N counts is $\sqrt{N}$.

Summary of errors

The BERM has a total probable error of ± 25% plus a calibration drift caused by the battery. However, the total probable error can be reduced to about ± 13% under the following conditions:

- A progeny filter is installed.
- A highly stable power supply is in use.
- The BERM is calibrated against a standard instrument with a ± 10% error.
- Background rate adjustments have been made.

Application

The discussion on errors assumes that the BERM is in equilibrium with the surrounding air. A number of factors affect the time required for the BERM to reach this equilibrium.

Filters

As discussed earlier, the installation of a simple radon progeny filter will limit the particles entering the ionization chamber to radon. Find a polyethylene plastic bag sealed on three sides that is large enough to hold the ionization chamber. Inflate it with air and tie it off at the neck with several turns of a wire tie. Observe the inflated bag over a period of about an hour to make sure that it has no pinhole leaks.

After you are satisfied that the bag is free of pinholes, open it and place the ionization chamber inside. Then inflate the bag again and again tie it off with several turns of the wire tie around cable this time. Attempt to hold as much air as possible inside the bag while you tie it off.

PARTS LIST

Figure 6 ratemeter circuit.
All resistors are ¼-watt, 5%.

R8—100,000 ohms, carbon composition
R9—100,000,000 ohms, carbon composition
R10, R13—2,200 ohms, carbon composition
R11—5000 to 10,000, 15-turn trimmer
R12—100 ohms, 15-turn trimmer

Capacitors

C5—470 pF silvered mica, selected (see text)
C6—10 µF, 15 volts, aluminum electrolytic, radial-leaded, value tested (see text)

Semiconductors

Q2—2N5566 dual JFET
D2, D3—diodes formed from 2N2222 transistors

Other components

M1—0 to 20µA analog moving-coil panel meter (see text)

Response time

Theoretically, if a constant concentration of radon could be introduced into the chamber, the alpha count rate would increase over a few hours before reaching a stable rate. Figure 9 is a plot of short-lived radon progeny dynamics, which affect alpha count ratio until equilibrium conditions are reached. The BERM's ionization chamber will typically stabilize in a few hours. The shortest time constant of the rate meter is 17 minutes.

Background rate

Even when BERM is taken outdoors where radon concentration is very low, it is likely that there will be some alpha activity in the chamber. It will be caused by the materials in the chamber itself as well by residual isotopes from the surrounding air which have attached themselves to the chamber walls.

Because this background activity is variable, it is advisable to check the background rate after cleaning the chamber. This is done by discharging high-voltage capacitor C1 and flushing the chamber with clean outside air. If possible, allow the chamber to remain outdoors for a day before performing the indoor measurement.

The background rate of the chamber is typically 20 to 60 counts per hour. Use the net counting rate—gross indoor rate minus outdoor rate—to calculate radon concentration, especially if the rates are similar.

Making a measurement

Although the BERM has an assumed large scale factor or calibration error, the instrument is still sensitive enough to detect even small amounts of radon, perhaps only a few times greater than that in outdoor air. It has sufficient dynamic range to remain linear up to several hundred counts per minute. Without a filter which improves accuracy but slows down its measurement, the BERM can be used anywhere in a house to identify the highest levels of radon concentration and the conditions that cause that level.

Vibration effects

As stated in Part 1 of this article, the BERM's ionization chamber is a very sensitive vibration sensor that will also respond to loud, low-frequency noises. Be suspicious of any unusually high readings if the chamber had just been inadvertently bumped against a solid object. After you have gained experience with BERM while it is connected to an oscilloscope, you will be able to see for yourself what level of vibration causes false detections.

Natural background

You can modify the BERM so that it will be capable of measuring radon concentration in the soil. To do this the radon monitor must be capable of measuring up to 200 counts per minute. This is done by replacing resistor R9 with one having a value that is only 10 % of the specified R9 value. Then:

- Place the ionization chamber in the plastic filter bag as previously described. (In this test the filter will act as a moisture barrier. The BERM is insensitive to changes in relative humidity, but condensation can provide a leakage path between the cathode lining and ground.)
- Dig a hole about 15 inches deep in dry ground.
- Place the bag-covered ionization chamber at the bottom of this hole to collect radon gas emitted from the soil and cover it with an inverted bucket. Then backfill the soil around the bucket to act as a seal.

This test should show that radon concentration in the ground is at least 100 times greater than that found in outdoor air. Compare the outdoor readings with those measured indoors with the same rate meter. If you have been unable to calibrate your BERM against a professional instrument, the readings taken in the ground will act as a useful reference. *If the amount of radon collected indoors is as much as 10 % of the level determined from the soil test, it is probable that a radon hazard exists.*

References

1. Brookins, Douglas G.: "The Indoor Radon Problem," Columbia University Press, New York, NY, 1990.
2. Lao, Kenneth: "Controlling Indoor Radon," Van Nostrand Reinhold, New York, NY, 1990.

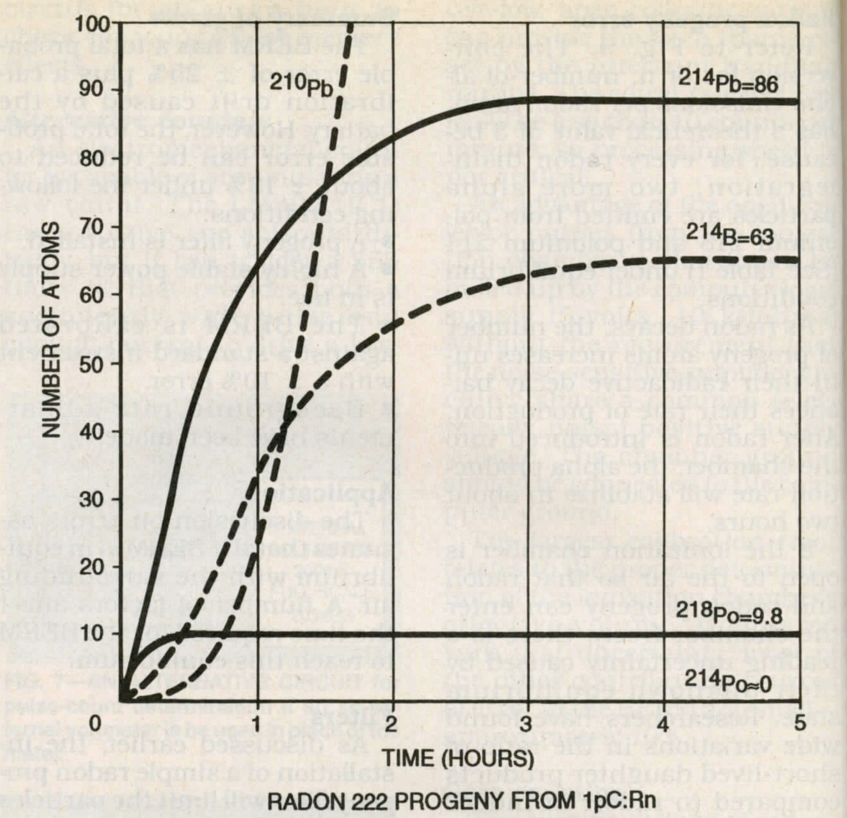

FIG. 9—PLOT OF RADON 222 PROGENY EMISSION OVER TIME VS. number of atoms.

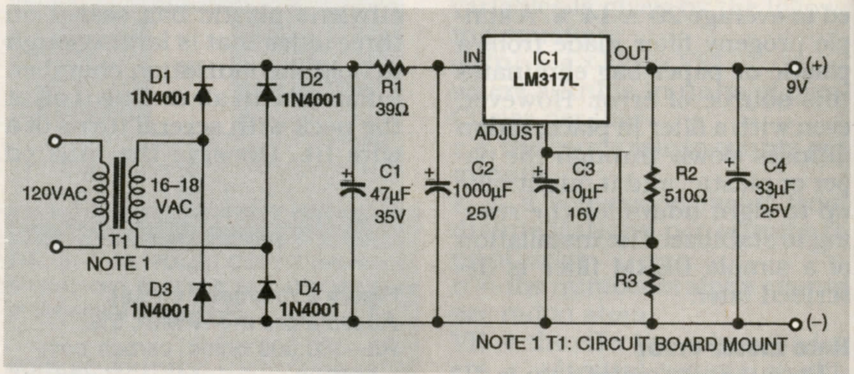

FIG. 10—THIS FILTERED POWER SUPPLY can replace a 9-volt transistor battery for powering the radon monitor.

Line power circuit

If you want to experiment with your BERM indoors or perform long-term testing, you might want to power it from the AC line rather than depend on disposable 9-volt batteries. An off-the-shelf AC-to-DC adaptor is not suitable for this application because it lacks the necessary filtering to eliminate noise interference. The circuit shown in Fig. 10 includes the necessary filtering. Ω