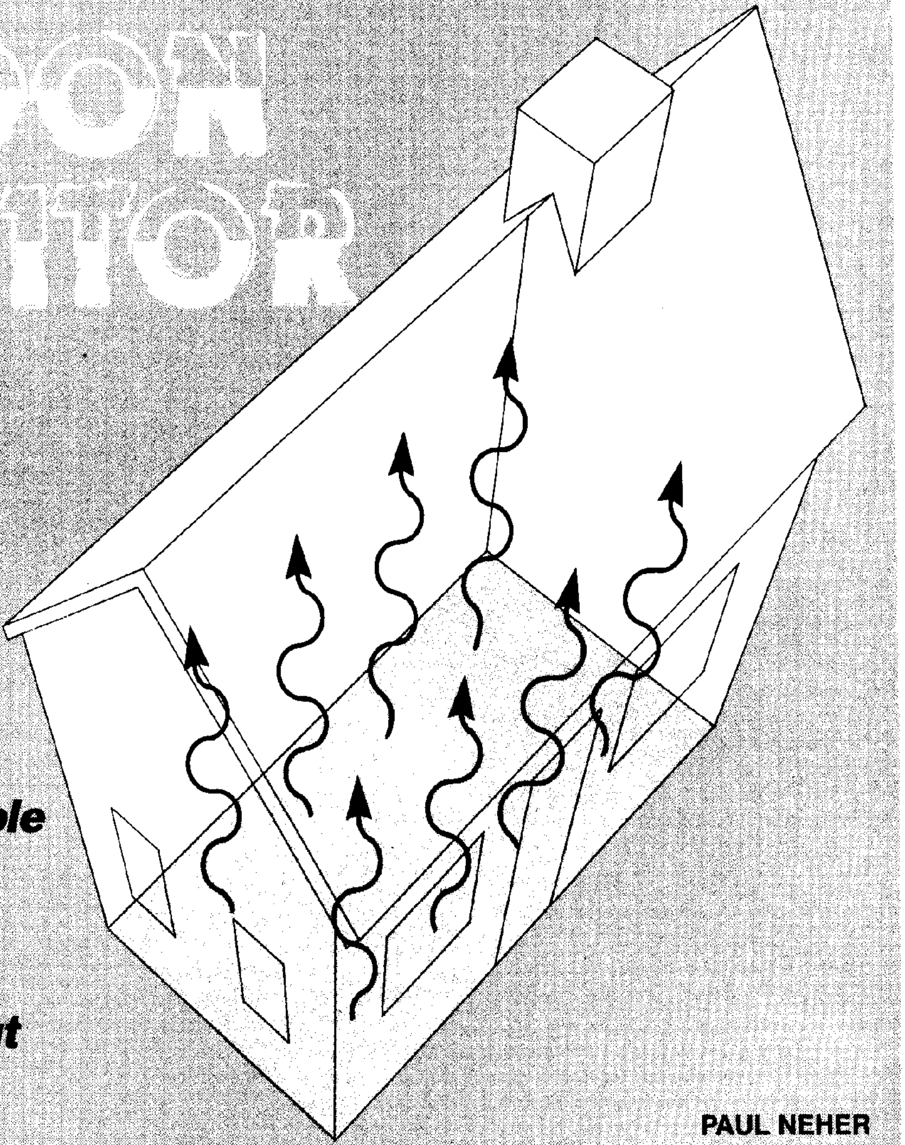
# RADON MONITOR



**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 of BERM's pulse counts to specific activity units.

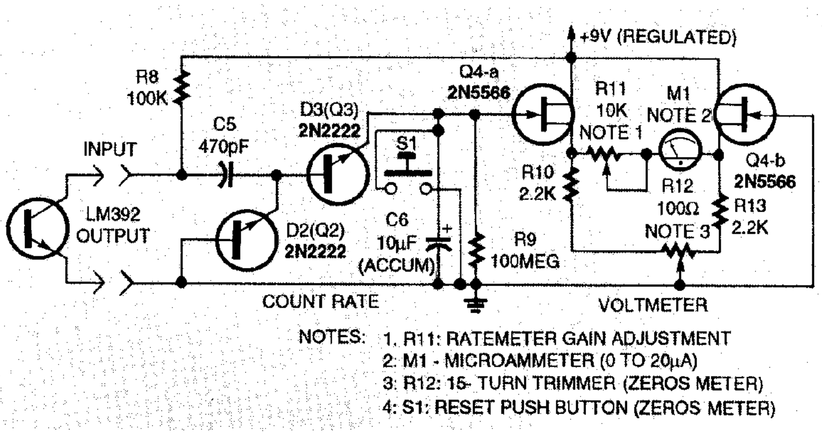


**FIG. 6—THIS PULSE-COUNT RATE circuit for the BERM is coupled by to the ionization chamber with a three-wide cable.**

### 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 × R9 × 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 %.

### 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.

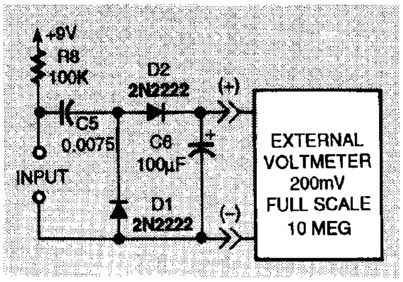


FIG. 7—AN ALTERNATIVE CIRCUIT for pulse-count determination if an an external voltmeter is be used in place of the meter.

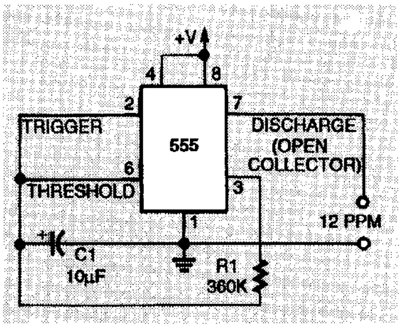


FIG. 8—THIS PULSE COUNT reference circuit can be used to calibrate the pulse-count rate circuit.

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.

## 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.

**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**
MI-O to 20μA analog moving-coil panel meter (see text)

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.

## 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

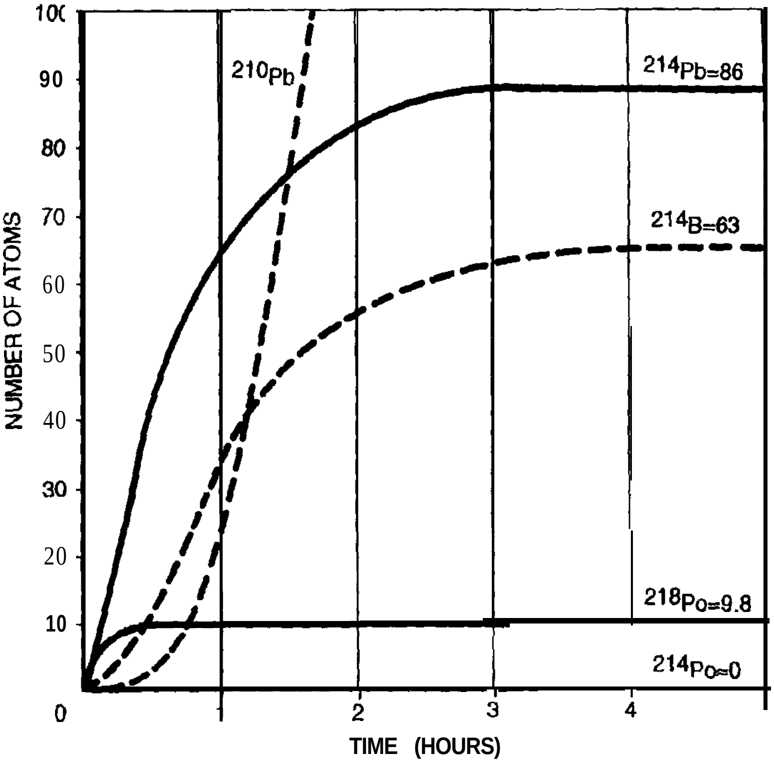
You can modify the BERM so that it will be capable of measuring radon concentration in the soil. To do this the radon monitor must be capable of measuring up to 200 counts per minute. This is done by replacing resistor R9 with one having a value that is only 10 % of the specified R9 value. Then:

- 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.*

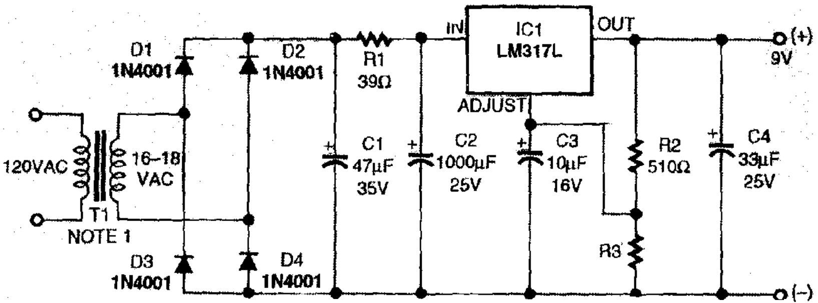
### Line power circuit

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



RADON 222 PROGENY FROM 1pC:Rn

FIG. Q-PLOT OF RADON 222 PROGENY EMISSION OVER TIME VS. number of atoms.



NOTE 1 T1: CIRCUIT BOARD MOUNT-

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

**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.