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Continuous Radiation Working-Level Detectors

By R. F. Droullard and R. F. Holub

UNITED STATES DEPARTMENT OF THE INTERIOR

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cm^2	square centimeter	mm	millimeter
cm^3	cubic centimeter	mm^2	square millimeter
cpm	count per minute	µm	micrometer
dis/min	disentegration per minute	µs	microsecond
h	hour	pCi/L	picocurie per liter
L	liter	pCi/(L/WL)	picocurie per liter per working level
L/min	liter per minute	pct	percent
MeV	million electron volts	V	volt
min	minute	WL	working level
mg	milligram	yr	year
mg/cm^2	milligram per square centimeter		

CONTINUOUS RADIATION WORKING-LEVEL DETECTORS

By R. F. Droullard[1] and R. F. Holub[2]

ABSTRACT

The Bureau of Mines has used gross alpha and gross beta detectors to continuously measure radiation working levels for a number of years. During this time, improvements have been made in the design and performance of continuous working-level (CWL) detectors. This report discusses the improved designs and some of the operating principles and applications of CWL detectors in the measurement of radon daughter products in mines and dwellings.

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INTRODUCTION

The inhalation of radon daughter products may result in lung cancer. These products can be an especially significant problem for underground miners in uranium and other types of mines where the daughter products of ^{222}Rn are always present in the mine atmosphere. Exposure to the ionizing radiation of ^{222}Rn is measured in working levels (9).[3] One working level denotes any combination of the short-lived radon daughter products in 1 L of air that will result in the ultimate emission of 1.3×10^5 MeV of alpha energy.

The most common method of measuring working-level exposures is to collect a grab sample on a filter and measure the alpha and/or beta activity. While this approach is satisfactory for some applications, it did not meet the needs of much of the radiation hazard research work performed by the Bureau, and so the Bureau initiated efforts to develop a CWL detector (5). A CWL detector differs from other automated samplers in that air sampling is continuous, whereas other methods use an electromechanical grab sampler that samples for predetermined periods. Radon daughter measurements using this latter method of sampling provide information that represents conditions at the time the sample is collected. Most of the CWL detectors discussed in this report have a response time that lags behind actual activity levels by about 1 h.

Earlier work by the Bureau on CWL detectors was reported in 1977 (4). Since that time, improvements have been made in CWL detector designs and applications (2, 6). CWL detectors developed by the Bureau and industry have been evaluated using the Bureau's radiation-hazard test facilities (3), and in operating mines and dwellings. This report provides updated information on the use of CWL detectors for measuring radon daughter activity over extended time periods.

THREE CWL DETECTOR DESIGNS AND MEASUREMENT METHODS

All but one of the CWL detectors discussed in this report measure the gross radon daughter activity collected on a filter by means of a vacuum pump. The type of radioactivity measured depends on the type of detector used. In any case, the detector output, in the form of pulses, is counted, and, through calibration, each count is assigned an equivalent amount of alpha energy, which is expressed in working levels. Three CWL detector designs developed by the Bureau are discussed in this section.

BACKSIDE OF FILTER COUNTING

Figure 1 shows an unassembled model B-100 CWL detector. Figure 2 shows an assembled detector mounted on a metal box that contains a high-voltage power supply for the Geiger-Mueller (GM) tube and an electronics system for signal processing.

In the model B-100 CWL detector, the beta activity of the radon daughters collected on the filter is measured by the GM tube from the back side of the filter collection surface. The primary reason for this method of measuring the activity is to provide an unobstructed pathway to the surface of the filter. This reduces problems with radon daughter plateout (removal of radon daughters from the air by their attachment to surfaces) and makes attachment of accessories less difficult. (Attachments for the B-100 detector are discussed in a later section.)

The B-100 detector uses a type-7311 GM tube with a diameter of 5.36 cm and a thickness of 1.53 cm. The tube has a mica window with an areal density of about 2 mg/cm^2. An aluminum foil is placed over the GM-tube window to prevent detection of alpha particles. The foil also helps to protect the interior of the GM-tube housing from moisture. The detector is operated with an anode resistance specified by the manufacturer and a

[3]Underlined numbers in parentheses refer to items in the list of references preceding the appendix.

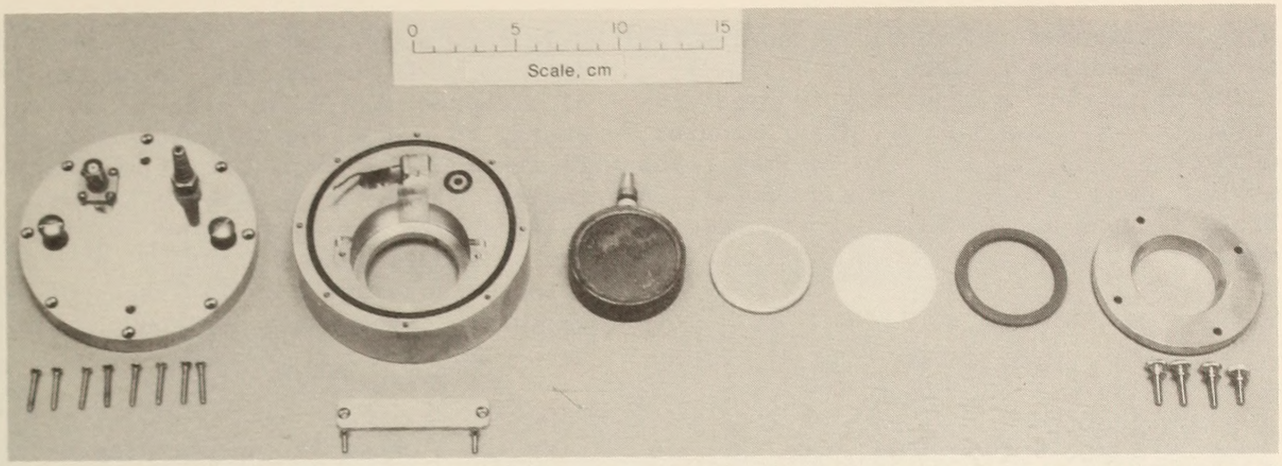

FIGURE 1. - Unassembled model B-100 CWL detector. From left to right: back cover plate with signal and air connectors, housing for Geiger-Mueller (GM) tube with GM tube clamp and O-ring seals, pancake-type GM tube, filter backup screen, glass-fiber filter, rubber filter gasket, and filter clamping plate with retaining screws.

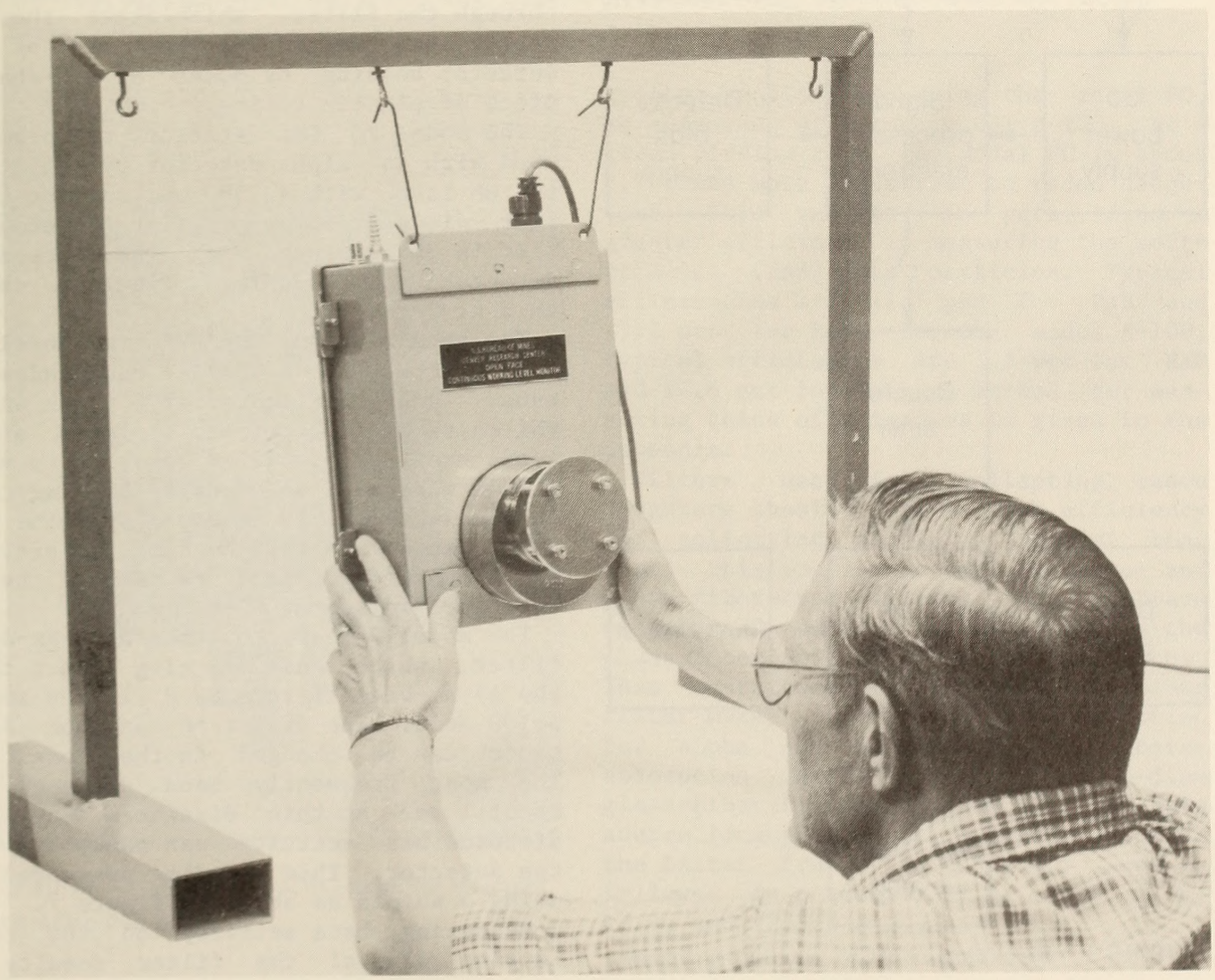

FIGURE 2. - Model B-100 CWL detector mounted on metal enclosure for associated electronics, with beta shield.

bias voltage determined by measuring the tube's operating plateau.

The signal-processing electronics consist of an amplifier, discriminator, dead-time control, and line driver. The system dead time is around 50 µs. A block diagram of a CWL monitoring system used by the Bureau is shown in figure 3.

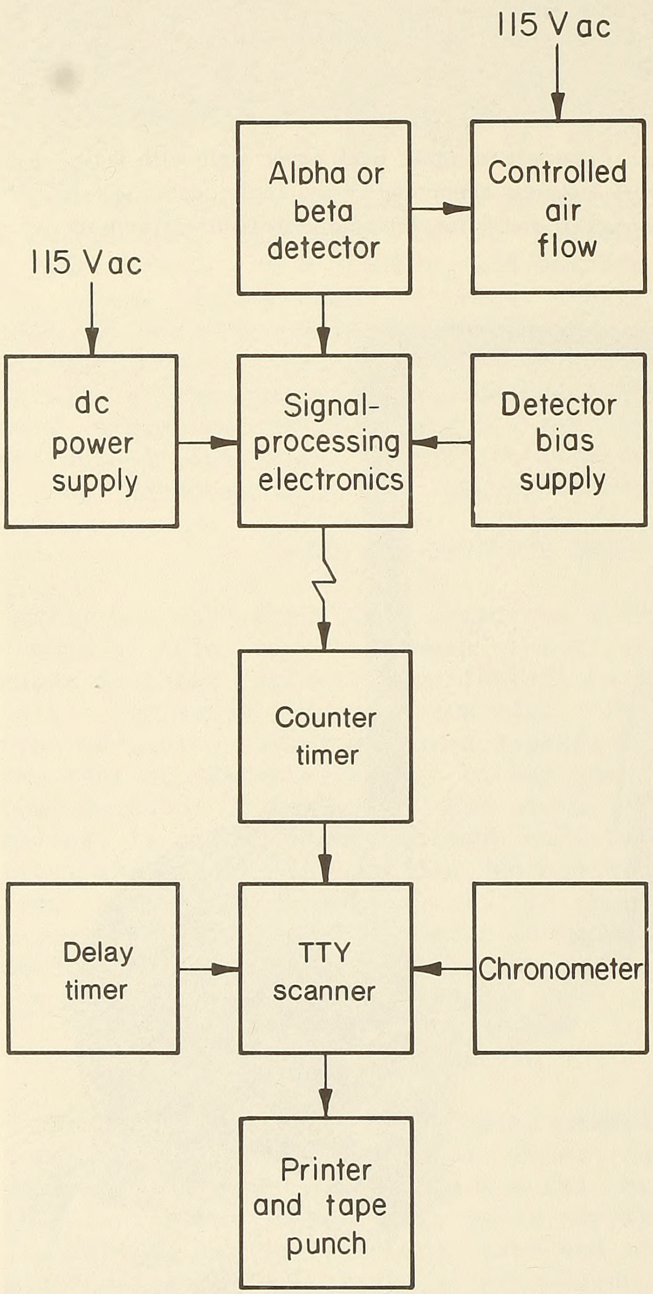

FIGURE 3. - Block diagram of CWL monitoring system.

In some applications of the B-100 CWL detector, beta particles from the decay of airborne ^{214}Bi (RaC) have sufficient energy to reach the GM tube through the filter and its backup screen. These unwanted particles can be eliminated by using a beta shield as shown in figure 2. The shield is spaced about 2 cm from the detector housing to avoid losses of radon daughters through plateout on the shield.

FILTER SURFACE COUNTING

Figure 4 shows an unassembled model FC CWL detector. Figure 5 shows an assembled model FC detector mounted on a metal box that contains the signal-processing electronics (same as those used with the B-100 detector). Collection air passes through the filter, which faces the detector, and then to the back side of the detector housing by means of a U-shaped piece of plastic tubing.

The model FC CWL detector can also be used with an alpha detector by replacing the GM tube with a 300-mm^2 surface barrier diode. An appropriate preamplifier is used along with the necessary detector bias supply. Figure 6 shows this arrangement.

The beta detector used in the model FC CWL detector is a type-7242 end-window GM tube. It has a diameter of 2.54 cm and a thickness of 1.33 cm. It operates at an anode voltage of 750 V and has a mica window with an areal density of 2 mg/cm^2. An aluminum foil is cemented over the GM-tube opening in the housing to prevent alpha measurements and to protect the GM tube from moisture.

The model FC detector uses a 25-mm-diam filter, which tends to clog sooner than the 47-mm-diam filters used in the model B-100 unit. The filter-to-detector distance can be changed in the model FC. The most frequently used distance is about 1 cm. At this distance, unwanted airborne beta activity can penetrate to the detector. This can be prevented by using a shield as shown in figure 7.

Measuring beta activity on the collection side of the filter results in

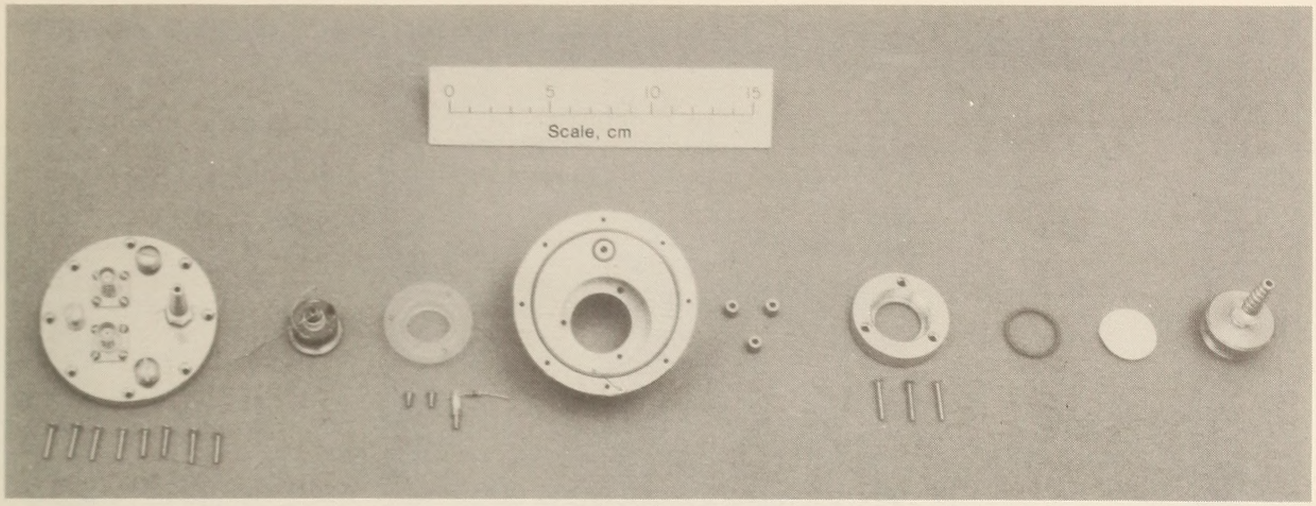

FIGURE 4. - Unassembled model FC CWL detector. From left to right: back cover plate with signal and air connectors, end-window GM tube, plastic mounting ring for GM tube, housing for GM tube, spacers, filter ring, O-ring filter gasket, glass-fiber filter, and filter holder with backup screen and tubing connector.

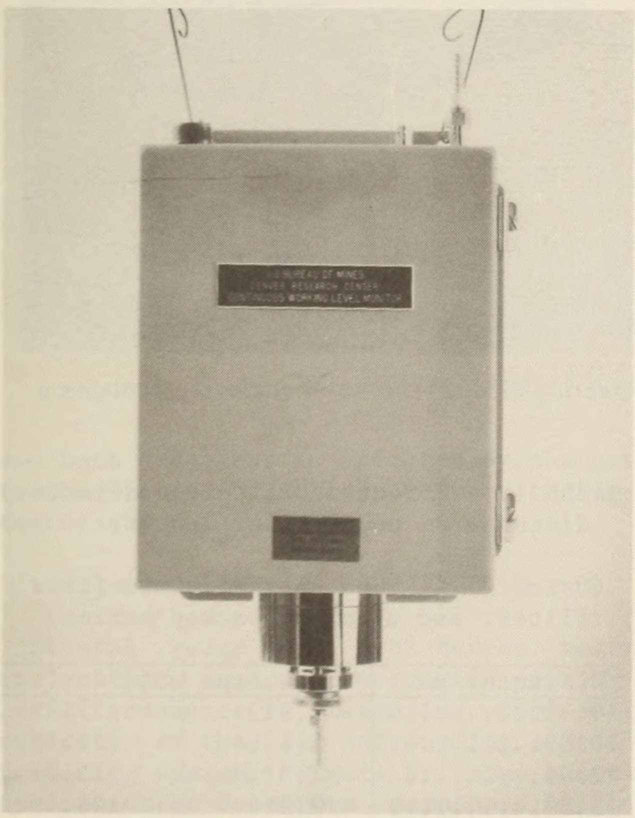

FIGURE 5. - Model FC CWL detector mounted on electronics box.

greater sensitivity using the model FC, as compared with the model B-100. At a given airflow rate, the model FC is about 2.7 times more sensitive to radon daughters. This results, in part, from a greater efficiency in measuring the softer ^{214}Pb (RaB) beta particles. Typical efficiencies are 11.7 pct for RaB and 13.2 pct for RaC. For the model B-100, typical efficiences are 3.5 pct for RaB and 10.6 pct for RaC. A method for measuring these efficiencies is given in the appendix.

Filters used for collecting radon daughters should have a high efficiency for collecting particles smaller than 1 µm; this applies to both membrane- and glass-fiber-type filters. The membrane filter is a surface collector, while the glass-fiber filter is a depth collector. This characteristic of the glass-fiber filter makes it prone to self-absorption for alpha and beta particles. Beta-absorption values for five 47-mm-diam glass-fiber filters, using a ^{210}Bi beta source located on the opposite side of the filter from a GM detector, were as follows, in percent: 17.5, 20.0, 17.6, 17.7, and 17.5.

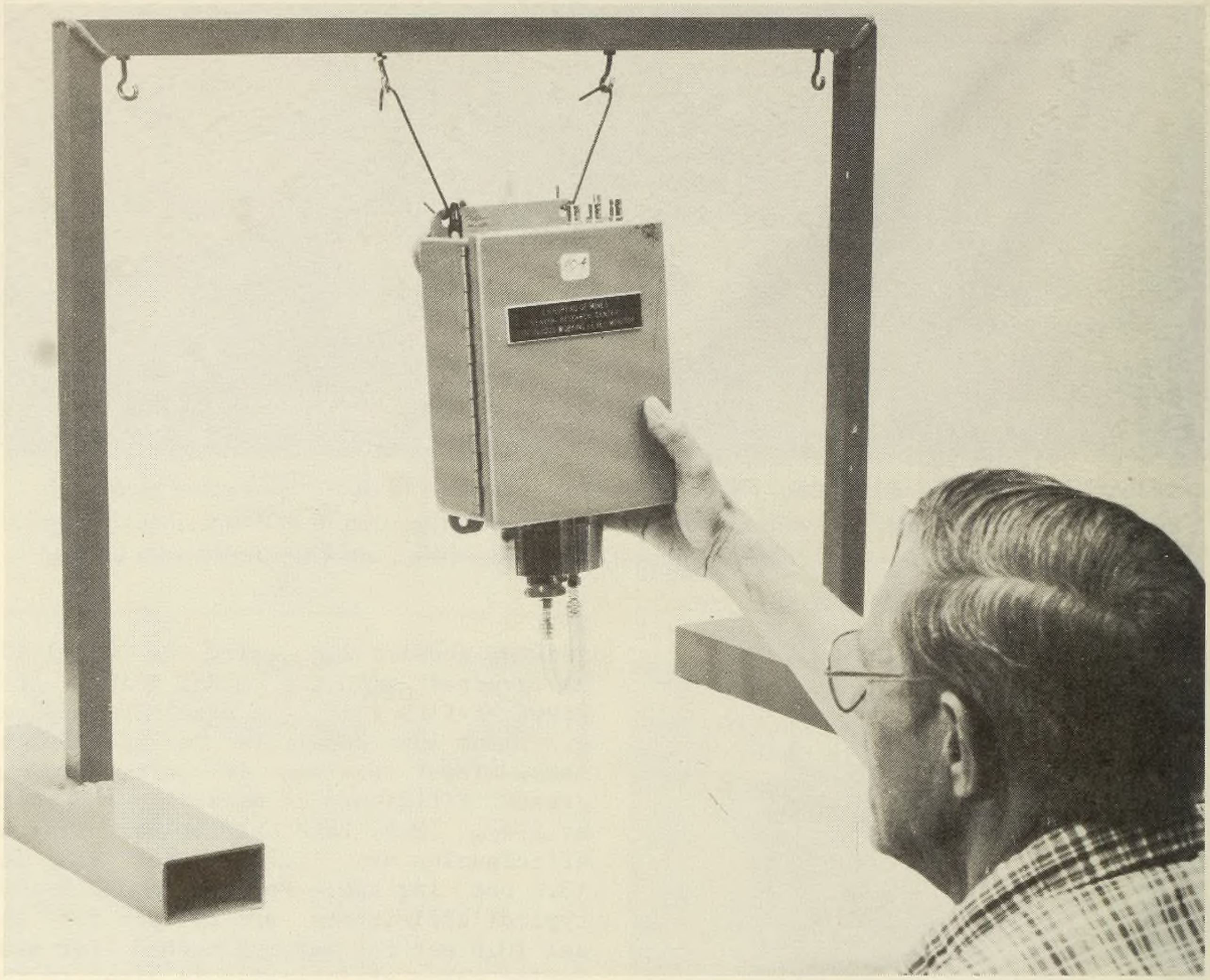

FIGURE 6. - Model FC CWL detector with alpha-detecting diode. The metal enclosure contains a preamplifier.

It is important to keep the filter-to-detector distance constant to maintain calibration in all CWL measuring systems. Table 1 shows the effect on count rate of changing the source-to-detector distance, using a ^{210}Bi beta source and a beta detector such as the type used in the model B-100. At the filter-to-detector distance used in the B-100, a 1-mm change in distance results in a change in the calibration factor of several percent. The filter must be kept in place against the filter backup screen. It will usually stay in place while air is applied to the CWL detector. The calibration of alpha

TABLE 1. - Effect of filter-to-detector distance on count rate

(Using ^{210}Bi beta source, glass-fiber filter, and aluminum backup screen)

Distance, mm	Count, cpm	Std dev, cpm
9.39..........	2,913	±27.3
10.89..........	2,736	±26.5
12.89..........	2,573	±25.7
15.89..........	2,314	±24.4
18.89..........	2,100	±23.3
21.89..........	1,861	±21.9
26.89..........	1,553	±20.1

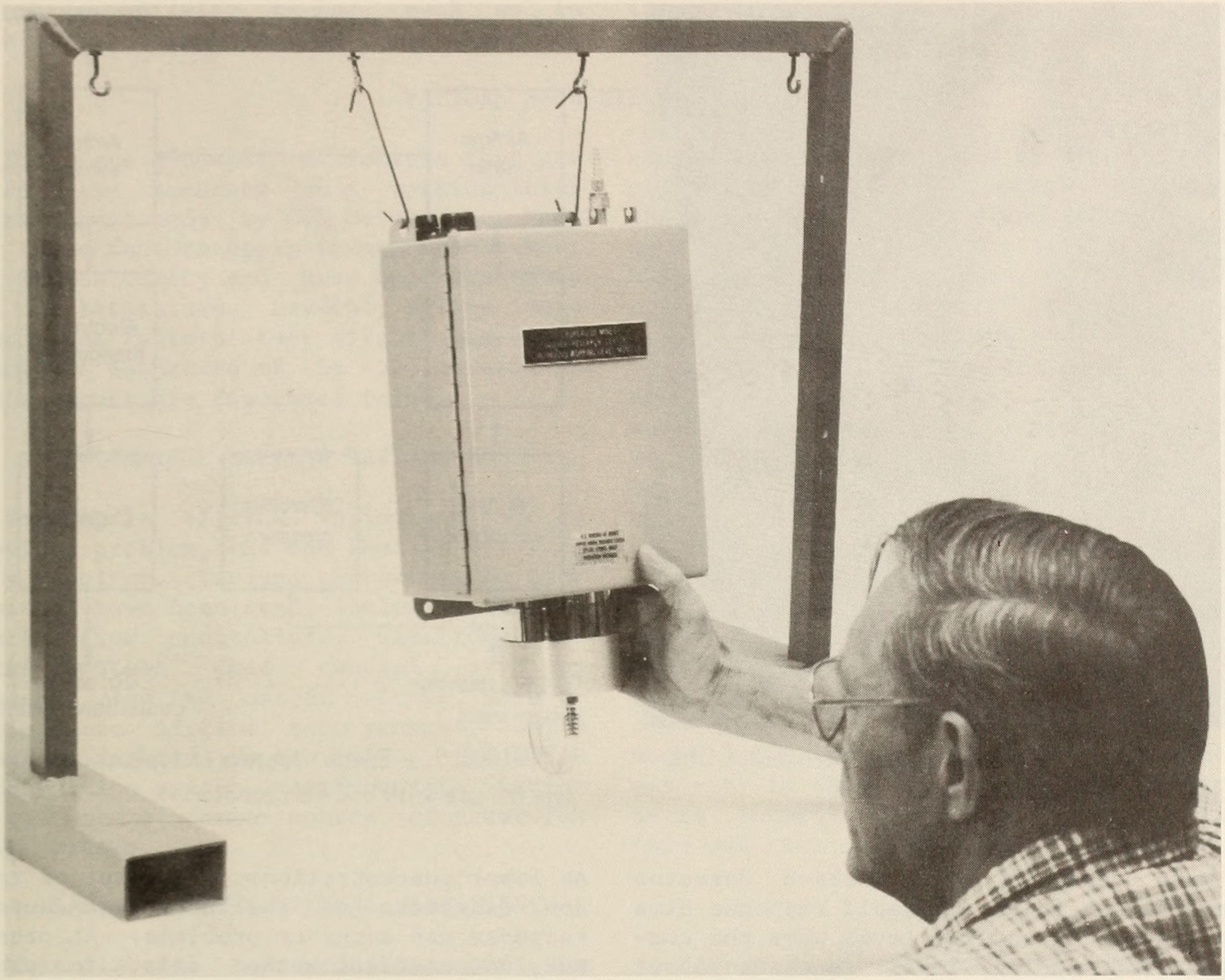

FIGURE 7. - Model FC CWL detector with beta shield.

and beta detectors is affected by changes in the air-path density between the detector and the source.

AMBIENT AIR COUNTING

Several years ago, the Bureau began evaluating a method of measuring working-level exposures by measuring the beta activity of the air surrounding a beta-detecting system. Figure 8 shows one of the prototype detectors developed by the Bureau and tested in the Bureau's experimental uranium mine. This detector, called the model Beta-8, consists of two counting sections. The lower section has four GM tubes operating in parallel with no shielding. These tubes can be seen at the lower end of the detector in figure 8. The upper section also has four GM tubes of the same type as the lower section, but these tubes are shielded against the ambient beta activity, resulting in gamma ray activity measurements only for this section. By subtracting the count from the upper section from the count from lower section, a fairly good approximation of the ambient beta activity can be made without the use of a filter and air system.

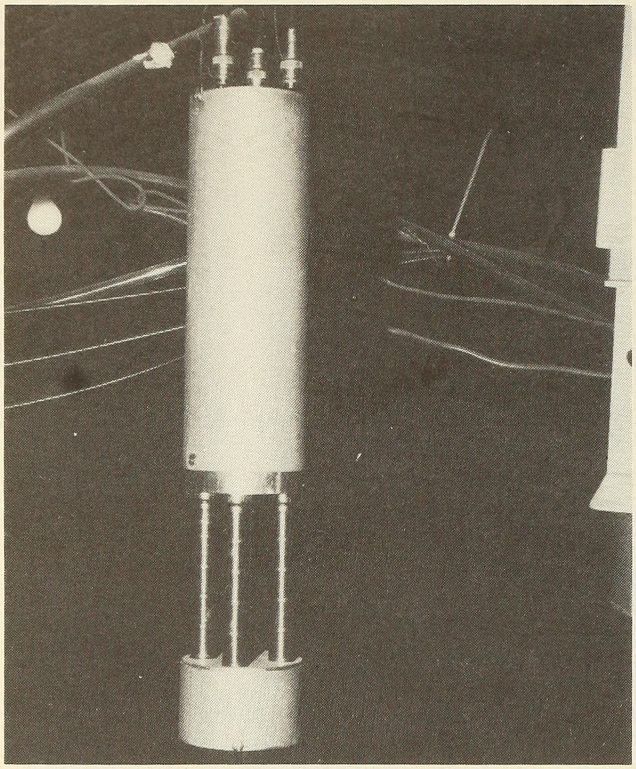

FIGURE 8. - Model Beta-8 experimental CWL detector.

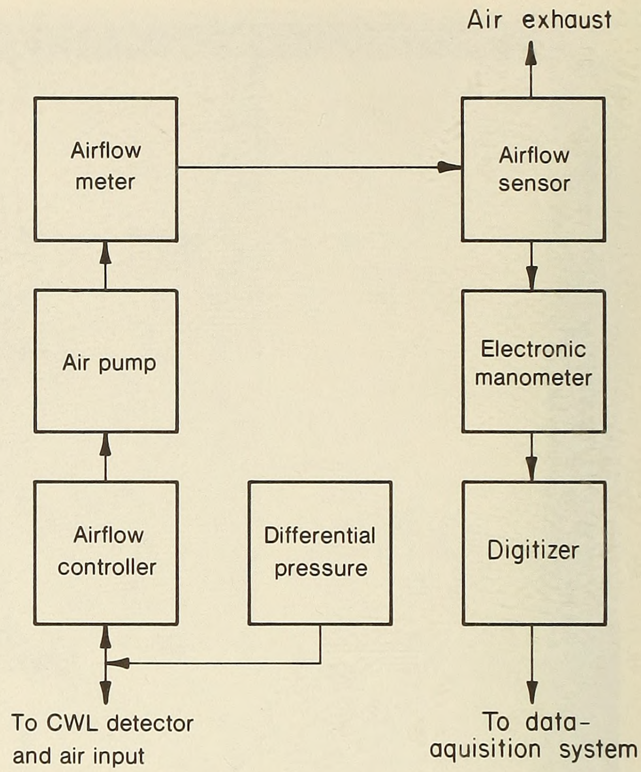

FIGURE 9. - Block diagram of typical air system for use with a CWL detector.

Mine tests of the Beta-8 detector showed that it has a rapid response time to changes in working level when the condensation nuclei level exceeds about 25,000 particles per cubic centimeter. At lower concentrations, plateout of radon daughters on the detector causes response and accuracy problems. At present, no practical method exists for preventing the radon daughter plateout.

AIR SYSTEMS

All methods for measuring radon daughters collected on a filter paper require a known air volume or volumetric flow rate. In most of its work with CWL detectors, the Bureau uses instrumentation to measure flow rate continuously. In addition, a mechanical flow controller is used to set and hold the flow rate at a fixed value over a wide range of differential pressures across the filter. Figure 9 shows a block diagram of a typical air system.

Continuous airflow rate measurements are made either by mass flow sensors and converted to volumetric flow rate or by direct measurement with volumetric flow sensors using a laminar flow rate. Flow rates are also checked with a dry test meter connected in an appropriate part of an air system.

Most of the air systems used in the Bureau's studies of CWL detectors include a pressure gauge to measure the differential pressure across the collection filter. The gauge serves two purposes: (1) It indicates the presence of a leak around a newly installed filter, and (2) it indicates when the filter should be changed because of clogging.

The sensitivity of a CWL detector is directly proportional to the airflow rate. In uranium mine applications, a flow rate of 1 to 2 L/min provides good sensitivity. For sites where the radon daughter activity is low, such as in dwellings, sampling flow rates can be increased to improve the statistical accuracy of the measured count.

FACTORS AFFECTING ACCURACY

There are a number of factors that can affect the accuracy of a working-level measurement made by CWL detectors. Many of these factors apply to any measurement of radioactivity and have been discussed in the literature. Several of the more important factors that affect the accuracy CWL detectors of the type covered in this report are discussed below.

VOLUMETRIC AIRFLOW VARIATIONS

Volumetric airflow variations are an obvious problem, but one that is not easily resolved. Various approaches to flow control have been used, including differential flow controllers, electromechanical systems that control air-pump speeds, and the use of either mass or volumetric airflow rate sensors, which usually require monitoring by the data-acquisition system. Airflow rate variations are a common source of error for CWL systems.

RADON DAUGHTER MIXTURE VARIATIONS

When airborne radon daughter mixtures differ from the mixture used for calibrating a gross-count CWL detector, the working-level measurement will have an error that is called inherent uncertainty. This error originates from assigning an average energy to each count measured when making the calibration. The degree of inherent uncertainty depends on how much the average energy per count differs from the calibration mixture and whether alpha or beta particles are being measured.

The degree of inherent uncertainty can be shown by a triangular graph (16-17, 19). Briefly, the graph represents all possible mixtures of RaA, (^{218}Po), RaB, and RaC equivalent to 1 WL. One leg of the triangle represents RaA activity in picocuries per liter per working level, and the other leg represents the RaB activity in the same units. RaC-C' (^{214}Bi and ^{214}Po) is represented by a line that originates at the midpoint of the hypotenuse and bisects the triangle. The line showing no inherent uncertainty passes through the mixture of RaA, RaB, and RaC upon which the calibration is based.

Figure 10 shows the inherent uncertainty triangle for a CWL detector measuring alpha particles. In this case, the error is quite low and can be ignored for most measurements. The error direction is toward overestimation of the working level as the radon daughter mixture becomes dominated by RaA. This provides some error compensation for plateout losses associated with radon daughter mixtures high in RaA and environments with relatively low concentrations of condensation nuclei.

The inherent uncertainty triangle for a model B-100 CWL detector measuring beta activity is shown in figure 11. Differences between the radon daughter mixture and the calibration mixture have a

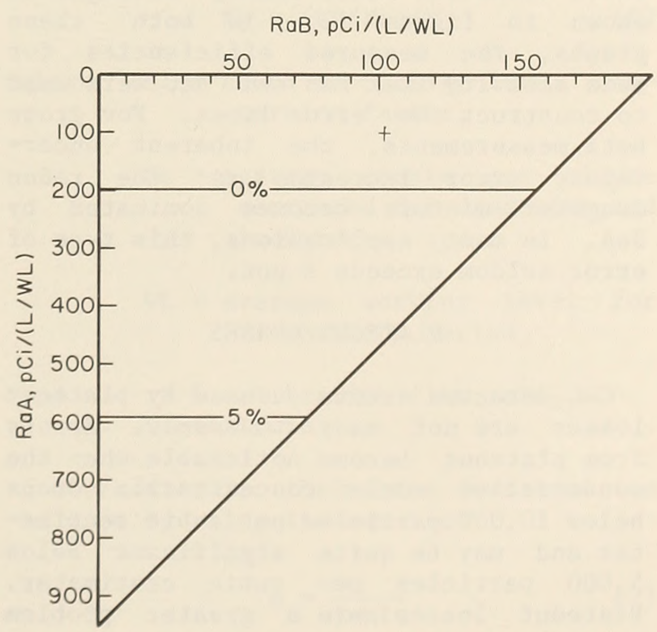

FIGURE 10. - Inherent uncertainty plot for a gross alpha CWL detector, showing percent inherent uncertainty. (Plus sign indicates equilibrium mixture.)

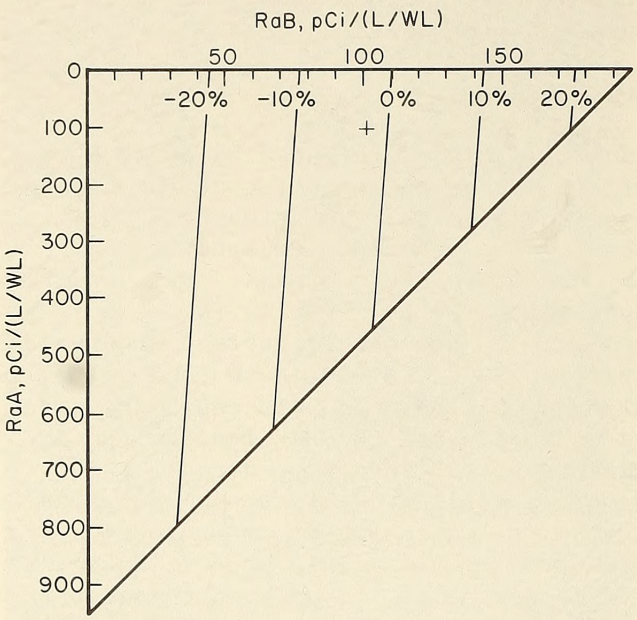

FIGURE 11. - Inherent uncertainty plot for a gross beta CWL detector counting from back side of filter, showing percent inherent uncertainty. (Plus sign indicates equilibrium mixture.)

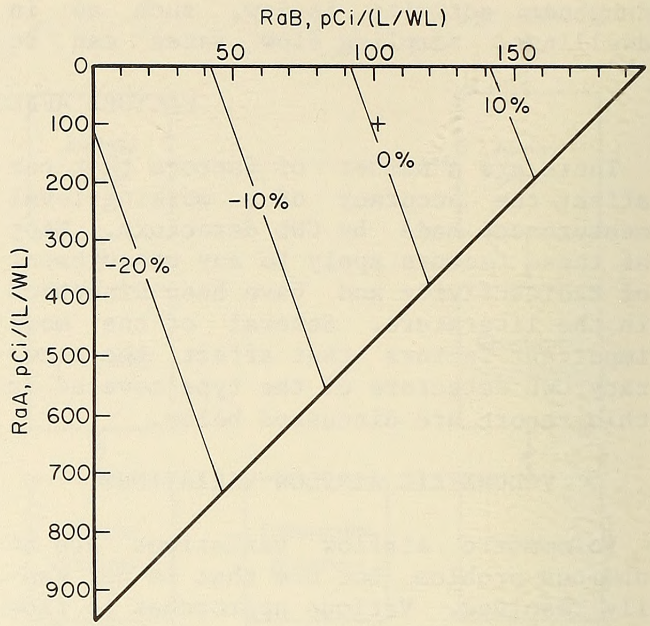

FIGURE 12. - Inherent uncertainty plot for a gross beta CWL detector counting from collection side of filter, showing percent inherent uncertainty. (Plus sign indicates equilibrium mixture.)

greater effect on this method of measuring working-level exposures. This is also true for the model FC CWL detector, whose inherent uncertainty triangle is shown in figure 12. In both these graphs, the measured efficiencies for beta activity from RaB and RaC were used to construct the error lines. For gross beta measurements, the inherent uncertainty error increases as the radon daughter mixture becomes dominated by RaA. In most applications, this type of error seldom exceeds 8 pct.

PLATEOUT LOSSES

CWL detector errors caused by plateout losses are not easy to assess. Errors from plateout become noticeable when the condensation nuclei concentration drops below 10,000 particles per cubic centimeter and may be quite significant below 5,000 particles per cubic centimeter. Plateout losses are a greater problem with detector systems designed to count the collection side of the filter; they do not pose a significant problem for beta detectors that measure from the back side of the filter.

OTHER SOURCES OF ERROR

Other sources of error previously mentioned include self-absorption by the filter and changes in the distance and air density between the collecting surface of the filter and the detector.

The use of depth filters, such as those made of glass fiber, results in some loss due to self-absorption. However, most of this loss is compensated for when the detector is calibrated. Surface filters, such as membrane filters, present little or no self-absorption problems with most aerosols when measurements are from the collection side of the filter. However, surface filters tend to clog much sooner than depth filters, making them less suitable for use in environments with relatively high smoke levels. Self-absorption problems encountered when counting from the back side of a filter are similar for both surface and depth filters.

Tests on the Bureau's model B-100 CWL detector show that there is a significant change in the count rate when the distance between the source and the beta detector is changed. (This effect is discussed in the previous section, "Filter Surface Counting.")

Dust and diesel smoke can affect the detector's response by increasing absorption of alpha and beta activity and by changing source-to-detector distances. This problem can be prevented by timely filter replacements.

In uranium mines, where CWL detectors are operated during periods when the ventilation system is off, significant amounts of ^{210}Bi activity will build up on the filter, causing an error in the measurements. This problem can be prevented by weekly filter changes.

Thoron daughters can also cause errors, but this has not been a problem in domestic mines.

CALIBRATION

CWL detectors are usually calibrated by operating them in an atmosphere where the radon daughter activity can be accurately determined. The best place to do this is in a properly designed radon test chamber, where the factors that affect calibration can be controlled reasonably well. Calibration can also be done onsite, such as in a mine, but a mine environment has constantly changing conditions that make calibration based on grab sampling difficult. This problem can be overcome by using a calibrated CWL detector to calibrate the unknown unit.

Prior to calibration, a system using a GM tube must be adjusted for operation at the midpoint of the detector plateau, and the system dead time must be known. For systems that use an alpha detector, a lower level discriminator must be set to a point where beta activity, as well as the detector noise, is not measured.

The first step in calibrating a system that uses a GM detector is to measure the background radiation (primarily gamma activity) at the operating site of the CWL detector. The Bureau uses a separate background detector operated near the CWL detector for this purpose. The gamma ray response between the two detectors is determined and used to correct the count from the CWL detector on a continuous basis. Alpha detectors should have insignificant background levels in most applications.

Before applying air to the CWL detector using a GM tube, the detector should be standardized with a gamma ray source, such as ^{137}Cs. The source should be placed at a fixed distance from the detector and the detector's response recorded for future reference. For systems using alpha detectors, a ^{230}Th source on a disk that replaces the filter paper can be used for standardization.

Following the standardization procedure, air at a known flow rate is applied to the CWL detector. After a period of 4 h or more in a controlled radon daughter atmosphere, the count rate is measured and corrected for dead-time losses and background. Modified Tsivoglou (21) or alpha spectroscopic methods are used to measure the levels of radon daughter activity. This information is converted to working-level values, and a count conversion factor is determined by the equation

$$K_F = (WL/Na)/F, \qquad (1)$$

where K_F = count-to-working-level conversion factor,

Na = average counts per minute corrected for dead time and background, cpm,

WL = average working level for calibration period,

and F = calibration flow rate, L/min.

Correction for the system dead time can be made by using the equation

$$N = \frac{n}{1-nt}, \qquad (2)$$

where N = true count rate, cpm,

n = observed count rate, cpm,

and t = dead time, min.

The dead time for the counting system can be measured using an oscilloscope.

Another method for determining the count-to-working-level conversion factor for beta detectors is given in the appendix.

ATTACHMENTS FOR MODEL B-100 CWL DETECTOR

The unobstructed filter-collection input of the model B-100 CWL detector facilitates attaching devices to modify the detector's response. One such device is shown in figure 13. Input tubes have been mounted on the filter clamp rings of two model B-100 units. One of the tubes has a 60-mesh wire screen (13) at its entrance. Figure 14 shows the effects of this screen relative to the amount of condensation nuclei in a test chamber atmosphere. The measurements were made with the chamber mixing fans off and with condensation nuclei generated by a nebulizer using tap water. The ratio of the working-level values measured by the two B-100 detectors (designated B-102 and B-101) reflects the amounts of attached and unattached radon daughter particles in the test chamber atmosphere.

Figure 15 represents similar measurements made in the Bureau's Twilight experimental uranium mine over a period of several days. The results show the effect of diesel smoke on the ratio of attached-to-unattached radon daughters.

Figure 16 shows two Zeleny tubes mounted on the filter clamp rings of two model B-100 detectors. The tubes are identical except for a charged wire along the axis of one of them (fig. 17). These

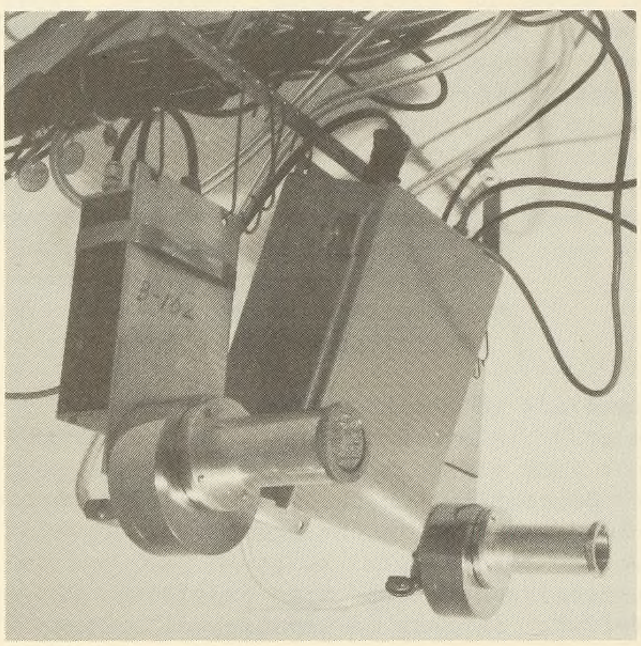

FIGURE 13. - Two model B-100 CWL detectors equipped with input tubes. Detector on left has a 60-mesh screen at the tube input.

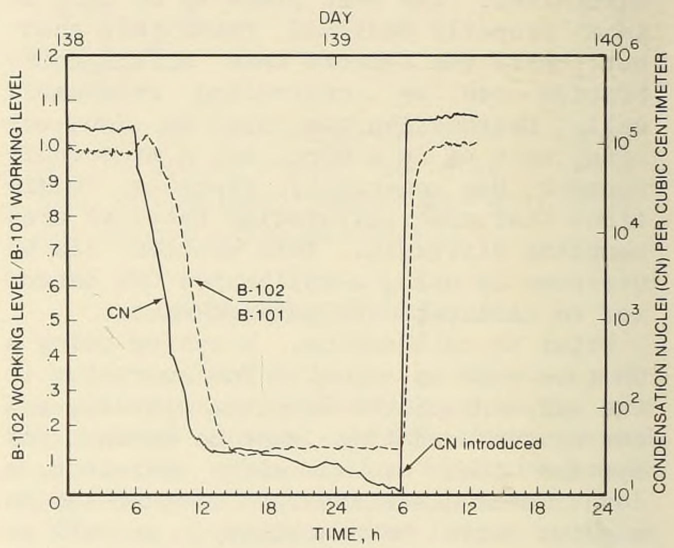

FIGURE 14. - Effect of input screen on attached-unattached radon daughter activity, with changes ir concentration of condensation nuclei.

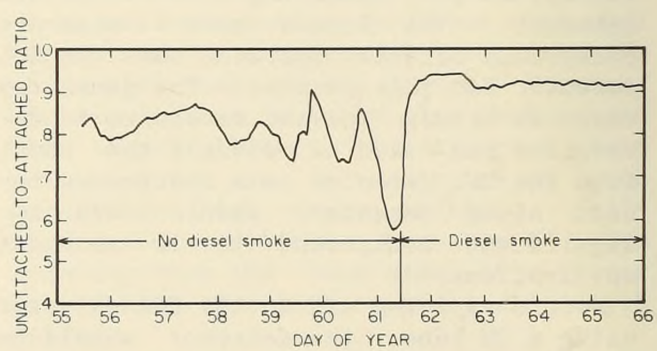

FIGURE 15. - Effect of input screen on attached-unattached radon daughter activity in the Twilight Mine.

FIGURE 16. - Two model B-100 CWL detectors equipped with Zeleny tubes. Detector on right contains a charged wire.

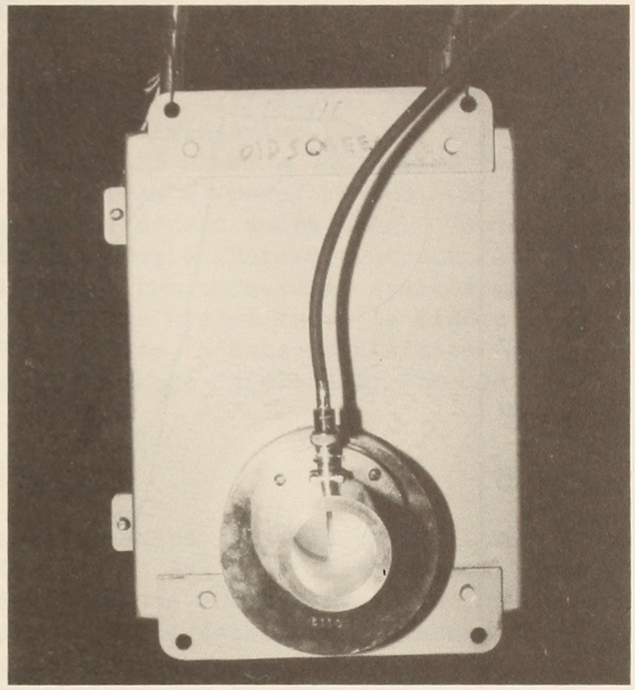

FIGURE 17. - Model B-100 CWL detector with Zeleny tube containing a charged wire.

tubes are patterned after work by Busigin (1). Figure 18 shows the results of operating with negative 1,000 V on the wire of detector B-102 and changing the amount of condensation nuclei in a radon test chamber under the same conditions as indicated above (for the screen measurements).

CWL DETECTOR APPLICATIONS

Commercial CWL monitors have been used primarily to monitor dwellings and radioactive waste disposal sites. Their use in mining has been very limited (14-15, 18).

The Bureau has used CWL monitors in its radiation hazards research program for over 8 yr (3, 11). CWL monitors have been especially useful in calibrating radon daughter dosimeters and in studies of radon daughter levels in various mine atmospheres. Franklin (10) describes an alarm system designed to warn of working-level exposures that exceed a preset value. Such a system is useful in providing mine operators with timely information on radiation levels at work sites and in main airways.

The Bureau's model B-100 CWL detector has been used to investigate the efficiency of a ventilating system equipped with a heat exchanger in removing radon daughters from the basement of a dwelling. Figure 19 shows the working-level measurements for a period of 2 weeks. During this time, air exchanges between the basement and the outside were normal except during the period marked on the graph when the heat-exchanger system was operating at 0.5 air exchanges per hour. The graph shows that the system was effective in lowering the working-level exposure to acceptable values for a portion of the house (where the bedrooms were).

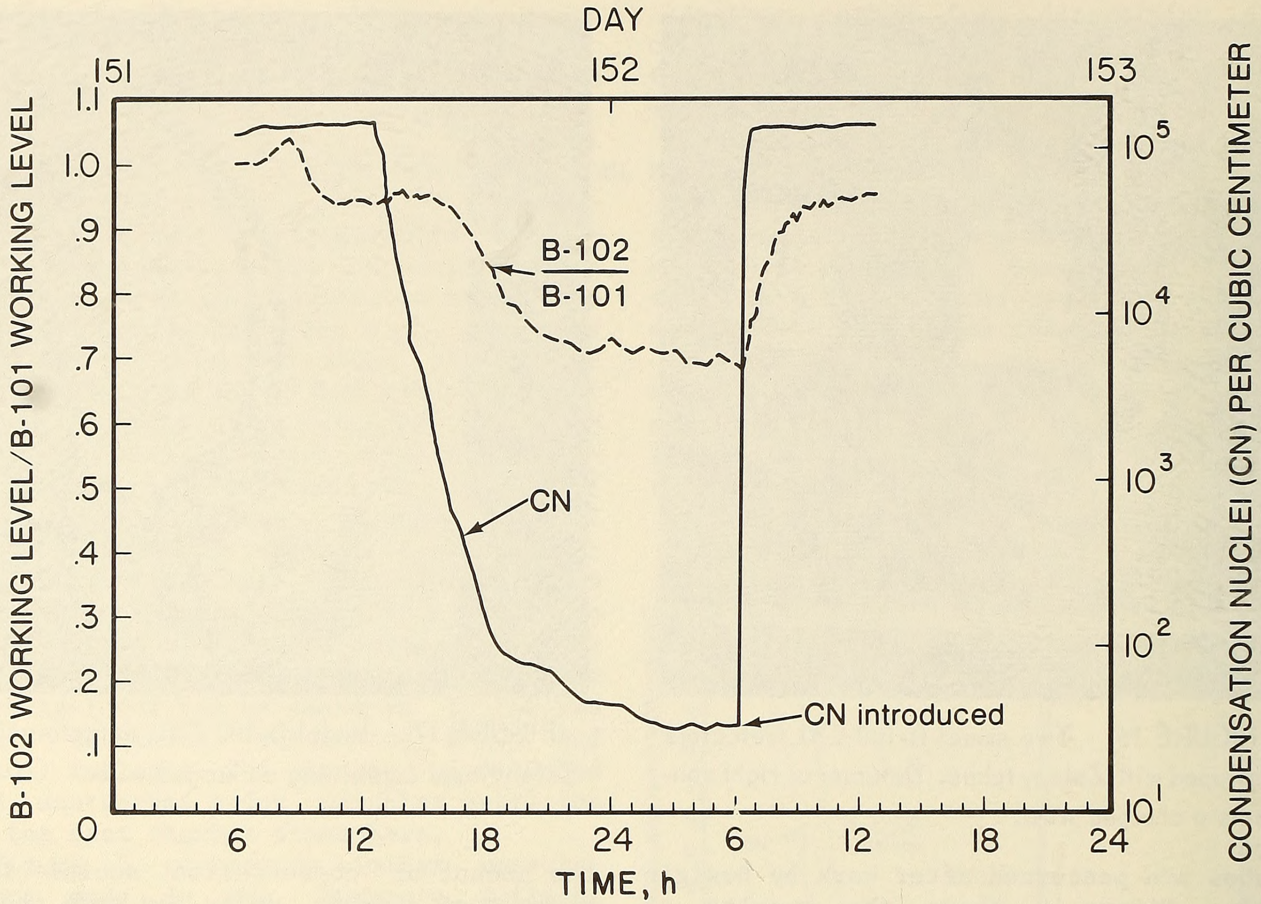

FIGURE 18. - Charged particle collection using a negatively charged wire in a Zeleny tube on a model B-100 CWL detector. A positive charge on the wire also results in the collection of radon daughters.

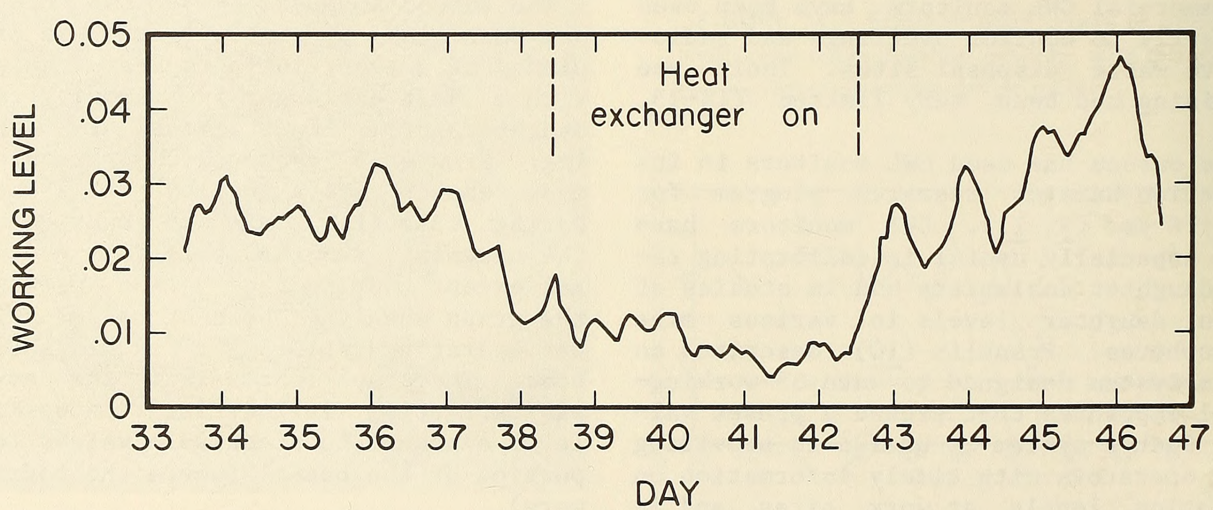

FIGURE 19. - Effect of a ventilation system using a heat exchanger on the working-level exposure in a dwelling.

COMMERCIAL CWL INSTRUMENTS

Figures 20 and 21 show two CWL monitoring systems that are available from commercial sources (7-8). Both of these systems measure alpha activity and use a membrane filter. Figure 22 shows a comparison of measurements made by a commercial (alpha) system and by the Bureau's model B-100 (beta) detector during the monitoring of a basement in a dwelling. The commercial system was operated with 60-min readout intervals, whereas the Bureau's system measured for 60 min and then delayed for 40 min. There is no significant difference between the results obtained using the two systems.

Figure 23 shows a commercial version of the Bureau's model B-100 CWL detector with the access doors open. The unit was built under a Bureau contract (20). Unlike the two commercial systems mentioned above, the system shown in figure 23 does not include a data-acquisition portion, which must be supplied by the user.

CONCLUSIONS

CWL detectors have been widely used in the Bureau's radiation-hazard research program for the past several years. Their application has been very useful in long-term calibration of personal dosimeters, working-level alarm systems for mines, and the study of long-term relationships between radon and radon daughters in mine atmospheres. Future applications are expected to include the use of these detectors in characterizing radon daughters and their relationship to aerosols found in mine environments.

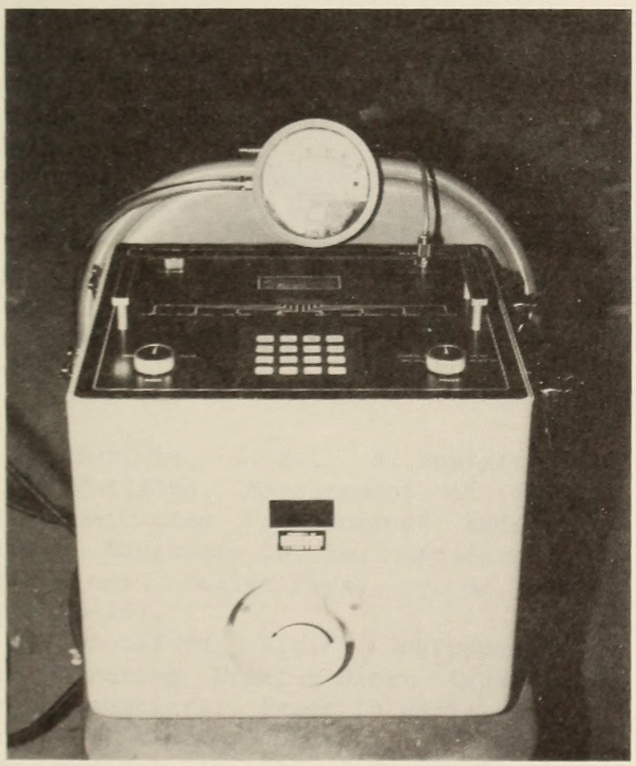

FIGURE 20. - A commercial CWL monitoring system in operation in a mine.

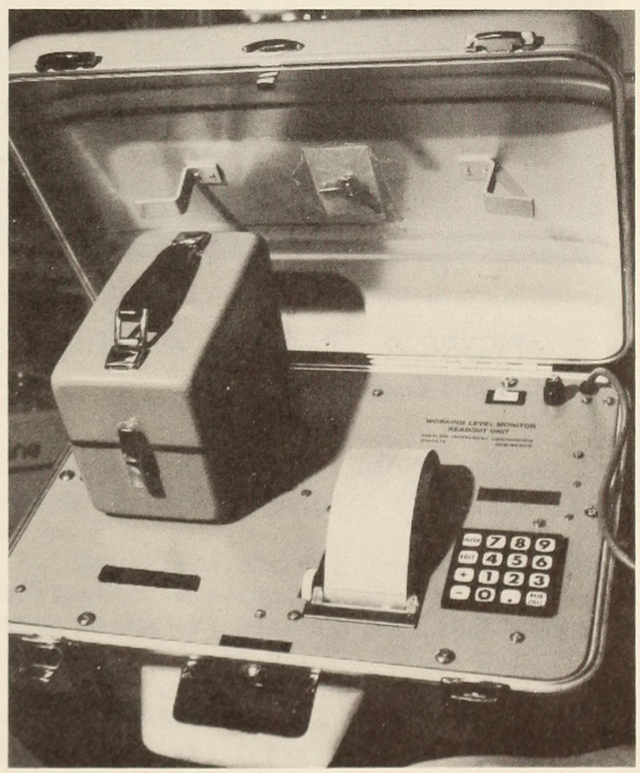

FIGURE 21. - A commercial CWL monitoring system undergoing tests in a Bureau laboratory.

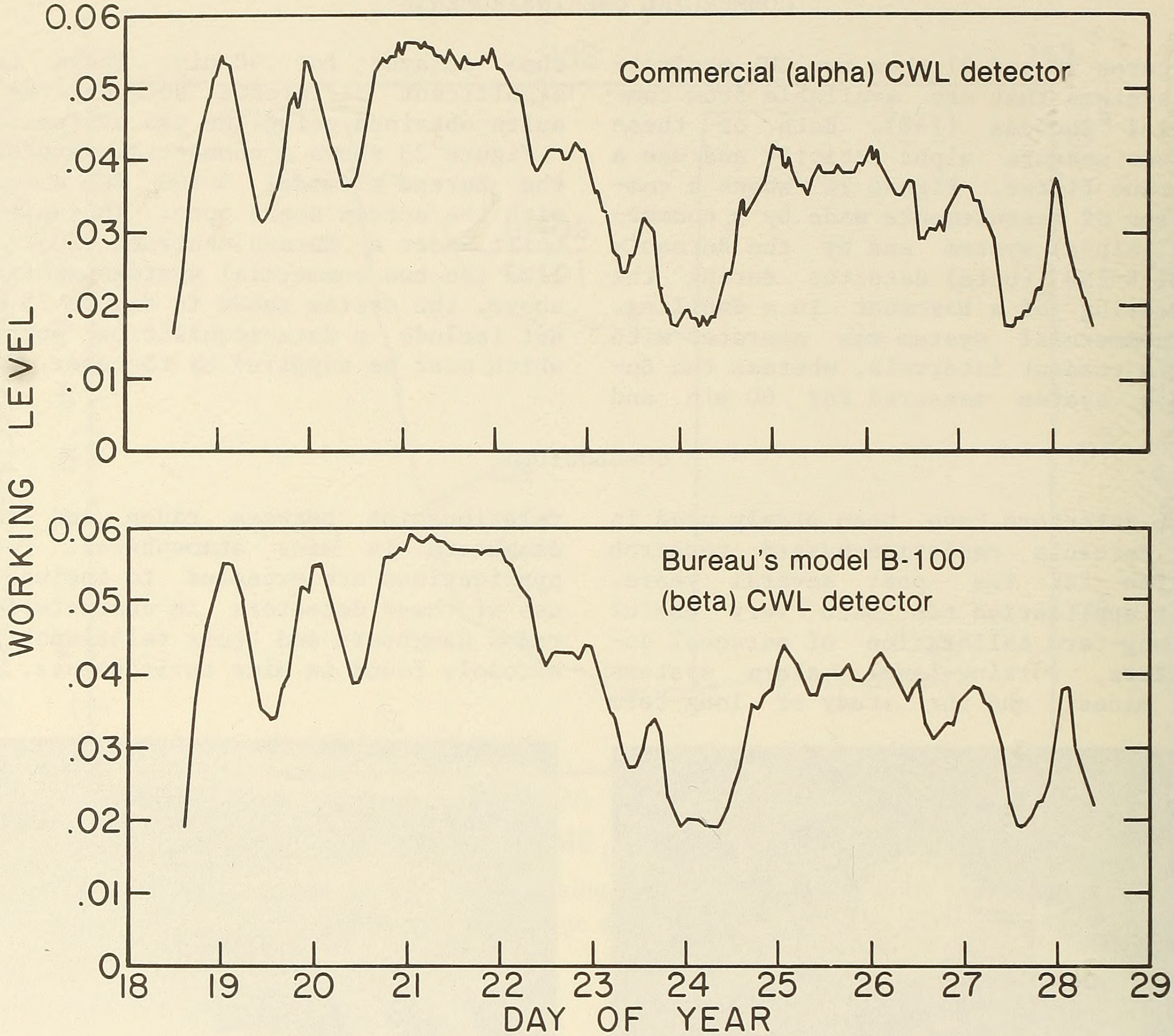

FIGURE 22. - Comparison of working-level values measured by alpha and beta CWL detectors in a dwelling.

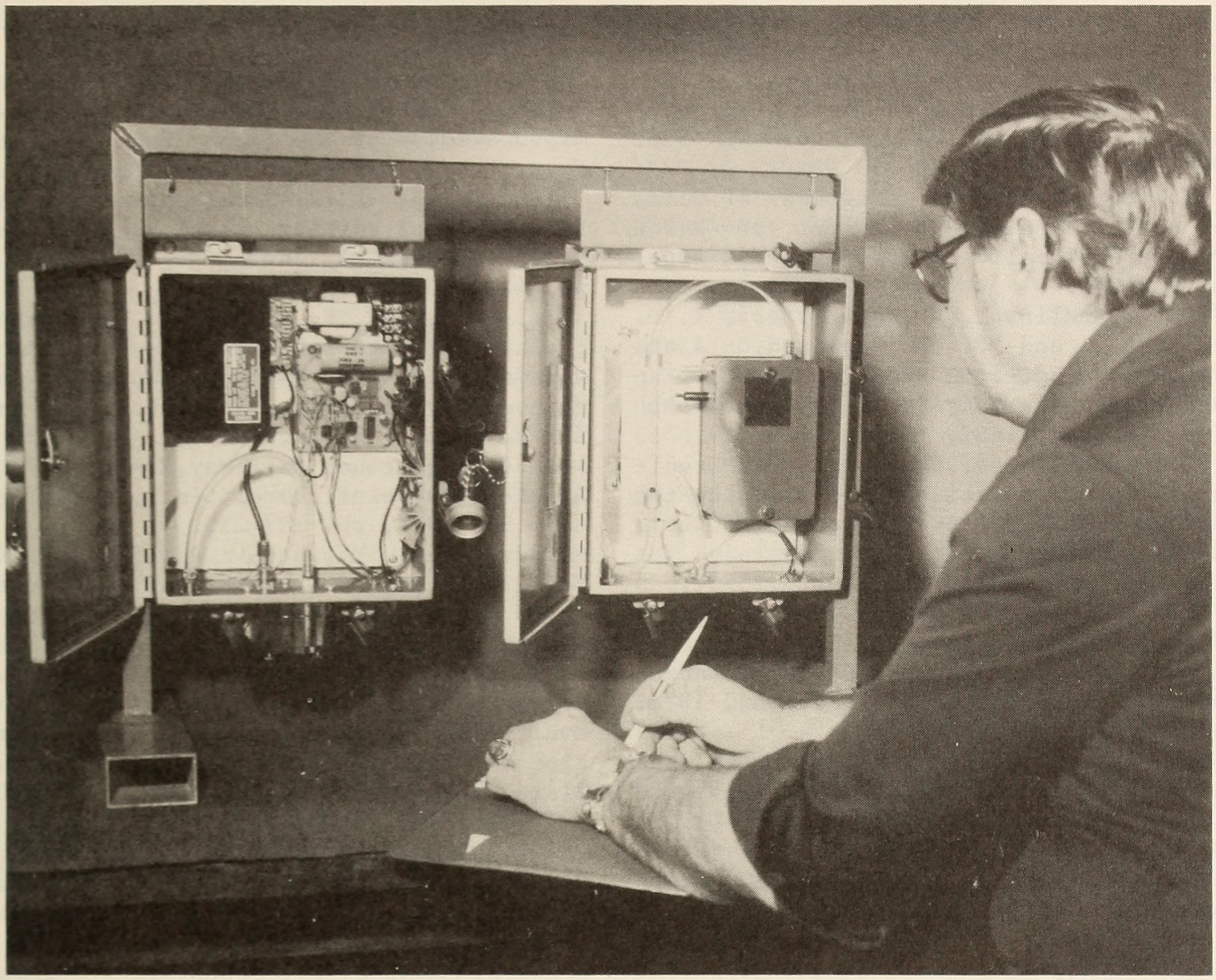

FIGURE 23. - Commercial version of model B-100 CWL detector (mounted at bottom of box at left). Metal box on right contains an air system for use with the CWL detector.

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APPENDIX.--METHOD FOR MEASURING EFFICIENCY OF A BETA DETECTOR

The efficiency of a beta detector for measuring ^{214}Pb and ^{214}Bi beta activity can be determined by the method described in this section.

The following equations are used:

$$I_1 = E_B N_{B_1} + E_C N_{C_1} \qquad (A-1)$$

and

$$I_2 = E_B N_{B_2} + E_C N_{C_2}, \qquad (A-2)$$

where I_1 = count measured in first counting period,

I_2 = count measured in second counting period,

E_B and E_C = unknown efficiencies for RaB and RaC,

and N_{B_1}, N_{C_1}, N_{B_2}, and N_{C_2} = number of atoms that decay on the filter paper during the two measurement periods.

The number of atoms (N_{B_1}, etc.) must be determined independently by measuring the radon daughter activity, using either the Tsivoglou (21) or alpha spectroscopic method.

Solving the linear simultaneous equations A-1 and A-2 for E_B and E_C provides the desired information. Repeated experiments show a reproducibility within ±10 pct of the individual efficiencies, reflecting the counting statistics in both I_1 and I_2 and in the determination of N_{B_1}, etc.

The accuracy of the beta efficiencies, E_B and E_C, can be checked by comparing their weighted sum to the steady-state equilibrium efficiency of a continuously operating beta detector using the following equation:

$$E_{B,\ TOTAL} = f_B \times E_B + f_C \times E_C \qquad (A-3)$$

where

$$f_B = \frac{N_B}{N_B + N_C}$$

and

$$f_C = \frac{N_C}{N_B + N_C}.$$

Both of these values are determined at the equilibrium at which the steady-state efficiency was determined.

A typical procedure for measuring the beta efficiencies is outlined below.

1. Measure RaA, RaB, and RaC using the modified Tsivoglou method.
2. Measure the background of the beta detector with no activity on the collection filter.
3. Collect a 15-min sample at a known flow rate.
4. Count the beta activity on the filter for 10 min, starting 2 min after the end of collection (2 min to 12 min). Make dead-time corrections and normalize to 1.0 L/min. Subtract background. The resulting difference is I_1.
5. Count the beta activity on the filter for 10 min, starting 17 min after the end of collection (17 min to 27 min). Make dead-time corrections and normalize to 1.0 L/min. Subtract background. This difference is I_2.
6. After completing the collection using the beta detector, measure the RaA, RaB, and RaC activity again.
7. Determine the mean RaA, RaB, and RaC values.
8. Calculate the N_B and N_C values for the 2-12 and 17-27 time intervals (steps 4 and 5), using equations from reference 12. These values become N_{B_1} and N_{C_2} for the 2-12 interval and N_{B_2} and N_{C_2} for the 17-27 interval.
9. Solving equations A-1 and A-2, find the determinant

$$DET = N_{B_1} \times N_{C_2} - N_2 \times N_{C_1},$$

then

$$E_B = \frac{I_1 \times N_{C_2} - I_2 \times N_{C_1}}{DET} \qquad (A-5)$$

and

$$E_C = \frac{I_2 \times N_{B_1} - I_1 \times N_{B_2}}{DET}. \qquad (A-6)$$

An example of this method for determining beta efficiencies for the model FC (beta) CWL detector is given below.

Step 1

RaA = 743.05 pCi/L

RaB = 303.17 pCi/L

RaC = 167.32 pCi/L

Exposure = 2.942 WL

Step 2

Background = 71.8 cpm

Steps 3-6

Flow rate = 1.893 L/min

Dead time = 47 µs

Gross count (2-12) = 38,720

Gross count (17-27) = 32,894

Net count (2-12) = 38,120

Net count (17-27) = 32,261

Count normalized to 1 L/min (2-12)

= 20,137

Count normalized to 1 L/min (17-27)

= 17,042

Steps 7-8

N_{B_1}(2-12) = 90,139 dis/min at 1 L/min

N_{C_1}(2-12) = 72,558 dis/min at 1 L/min

N_{B_2}(17-27) = 62,700 dis/min at 1 L/min

N_{C_2}(17-27) = 73,477 dis/min at 1 L/min

Step 9

DET = (90,139)(73,477) - (62,700)(72,558)

$$E_B = \frac{(20,137)(73,477) - (17,042)(72,558)}{DET}$$

= 0.1172 (11.72 pct)

$$E_C = \frac{(17,042)(90,139) - (20,137)(62,700)}{DET}$$

= 0.1319 (13.19 pct)

Using the above values of RaA, RaB, and RaC (from step 1) and normalizing them to 1 WL and 1 L/min, the equilibrium filter activity would be as follows:

$N_{B_{eq}}$ = 11,399 dis/min,

$N_{C_{eq}}$ = 14,987 dis/min,

and $N_{B_{eq}} + N_{C_{eq}}$ = 26,386 dis/min.

Using equation A-3, the total beta count can be calculated as follows:

$E_{B,\ TOTAL}$ = (0.432)(0.1172)

+ (0.568)(0.1319)

= 0.1255 (12.55 pct).

In this example, 12.55 pct of 26,326 dis/min gives a count rate of 3,313 cpm, and the reciprocal of this number gives a count-to-working-level conversion factor of 0.000302. The conversion factor determined by the usual calibration method described in the main text was 0.000307, which is in good agreement with the value determined using the detector beta efficiencies.

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